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RADC-TR-84-203
Final Technical Report
October 1984



ARTIFICIAL INTELLIGENCE APPLICATIONS TO TESTABILITY

Boeing Aerospace Company

Henry Lahore

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1.0 INTRODUCTION

1.1 BACKGROUND

The cost effectiveness of fault detection and isolation techniques used in electronic systems is a present concern of the military, now that testing exceeds 25% of the total life cycle cost of a system (1). Problems include assuring adequate failure coverage by Built-In Test and Automatic Test Equipment (BIT/ATE), reducing false alarms, isolating intermittent failures, and reducing maintenance training requirements.

1.2 OBJECTIVES

This study provides the foundation for a logical and cost-effective program for applying Artificial Intelligence to testability. Emphasis is on those artificial intelligence (AI) techniques capable of practical application to testability problems immediately or with low risk development within three to five years.

1.3 SCOPE OF STUDY

This study surveyed AI techniques for potential application to electronic testability. Fault detection and fault isolation are primarily accomplished in military electronic systems with Built-in Test (BIT) and Automatic Test Equipment (ATE). The extent of current use of AI in BIT and ATE was identified. The current problems in testability were identified, potential AI solutions were analyzed and near term opportunities were evaluated.

The survey considered a wide variety of military electronics and was concerned with use of artificial intelligence techniques that could provide improvements to functional and diagnostic testing of systems, boxes, and cards that must operate in a wide range of environments. That equipment must generally be very reliable while operating under rugged environmental conditions since the liability of malfunction is often of military or life importance. The electronics costs are very high while production volume is typically low. It should be noted that testability concerns for commercial systems are different for a majority of these characteristics. The largest differences are in production quantity and use environment. This study addresses only the military applications of Artificial Intelligence to testability

1.4 REPORT ORGANIZATION

The following sections describe the tasks performed for this study and briefly summarize the findings. Each subsection corresponds to a major section of this report.

1.4.1 Survey of AI Techniques

A survey was made of existing and developing AI techniques by literature search and interviews with national AI-Testability experts. A summary of the various AI techniques investigated and their applicability to testability are provided in section 2.0. The bibliography and industry survey appendices contain the details of all parts of the survey.

The AI techniques survey included all of the standard AI techniques, of which the following were found to have near term application to testability:

- o Expert Consulting Systems
- o Intelligent Retrieval from Data Base
- o Perception

o Machine Learning

A restricted version of Machine Learning was added to the initial list as it proved to be a very cost effective way of creating types of expert systems for problems which can be expressed in a tabular format, as is true for many maintenance problems.

The other techniques either were not well enough developed, did not have any application, would not produce a cost effective application, or were not appropriate for low volume military electronics. These included:

- o Theorem Proving
- o Natural Language Processing
- o Robotics
- o Automatic Programming
- o Modeling
- o Computer-Aided Instruction

1.4.2 Survey of Existing and Developing ATE/BIT

The two primary methods of testing military electronics are Built-In Test (BIT), and Automatic Test Equipment (ATE). The BIT portion of military electronics adds 2% to 20% additional hardware to confirm the functioning of 90% to 100% of the electronics and sometimes provide fault isolation. ATE is used for off-line, out of context test of a unit, generally not performed in the field.

Many possible AI applications were found for these two areas, but only a few were found to be of low enough risk and high enough benefit to warrant military R&D activity. The results of the ATE/BIT survey, in section 3.0, showed it to be much more cost effective to use AI techniques to eliminate the source of a testability problem (in the box or system) than to focus on the resulting symptom (i.e., better diagnosis tools or better ATE). The initial evaluations of the AI applications are documented in a matrix in section 5.1. Extensive references are contained in the bibliography and industry appendices.

1.4.3 Survey of Testability Applications

This applications survey included the following six possible testability improvement areas with a potential for near term application with, or as part of, an AI approach:

- o Self improving diagnostics
- o More effective fault detection and isolation
- o Discrimination between false alarms and intermittent faults
- o Reduction of skills required for maintenance
- o Integrated diagnostics
- o Design for testability

Evolutionary progress is being made in these areas. All provides tools which can speed up this evolution by improving information management.

1.4.4 Potential AI Solutions to Problems

Section 5.0 discusses the initial AI application analysis for military needs. Current testability problems were identified and potential AI applications to those problems evaluated. The following testability applications of Artificial Intelligence were specifically identified for investigation:

- o Computer-Aided Preliminary Design for Testability
- o Smart Built-In Test
- o Smart System Integrated Test
- o Maintenance Expert Box Level
- Maintenance Expert System Level
- Maintenance Expert System Level with Smart Bit/Self Improving Diagnostics
- o Analog Automatic Test Program Generation
- o Smart Bench (Computer Aided Bench Testing that learns diagnostics)
- o Digital Automatic Test Program Generation with Machine Learning

It was found that all of these application opportunities could be used with or developed by engineering work stations (EWS), which are becoming available directly to designers. EWS would allow low cost development and widespread use. Detailed discussions that typically include charts of evolutionary development are presented for each opportunity.

1.4.5 Final Evaluation

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A ranking of AI opportunities was made based on seven criteria for life cycle cost (LCC) impact as well nine other risk/cost and benefits associated with the development of each.

1.4.6 Study Findings and Recommendations

The primary message in section 7.0 is that curing testability problems, not just their symptoms, is a goal that is common to all the applications investigated in section 5.0, and that AI can provide hardware and software tools necessary to improve information capture, flow and processing. A more detailed presentation of study findings and recommendations is also included in that section. The primary recommendation made is for a phased evolution of several applications that emphasizes common support hardware and software for developers and end users.

1.4.7 References

The documents specifically referenced by the report are listed in section 8.1. Other reference material which contributed to this study is listed in the annotated bibliography of section 8.2.4 which is organized by subject (i.e., BIT/ATE, Maintenance Experts) and contains material of interest to readers who want a broader set of recent information on

All and testability. Items found by the survey which were several years old or only of theoretical interest are not included.

A list of the people interviewed is provided in section 8.3. The recommendations of four relevant test studies in 1983 provided in section 8.3 give a perspective from which to view the recommendations of this study.

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2.0 SURVEY OF AI TECHNIQUES

A survey was made of eleven AI techniques in order to judge their potential applicability to testability when used singly or in combinations. A wide variation was found in the maturity of development between the techniques. The findings, summarized below, show the wide variance in potential between the techniques. The specific, numbered references in this document can be found in section 8.1. Many other relevant references, not specifically addressed in this section but lending support to our findings, are found in the annotated bibliography, section 8.2. The conclusions reached as a result of the AI survey are in section 2.12.

THEOREM PROVING: There is currently no active work in this area, and no direct need is seen for its use in testability applications that are not now being solved by other means.

NATURAL LANGUAGE PROCESSING is a very active, but as yet immature, area. No substantial cost savings could be expected to result from testability applications, but worker productivity would increase.

INTELLIGENT RETRIEVAL FROM DATA BASES is being developed by more than 30 groups, and there should be substantial incremental development during the next few years. This technique improves testability by improving efficiency of data base search operations.

EXPERT CONSULTING SYSTEMS is the hottest AI topic with a number of commercial successes demonstrated and many military developments are currently underway. Maintenance expert systems are expensive to implement, but there appear to be approaches that avoid the knowledge engineering bottleneck. Metarules and machine learning have the potential to substantially reduce costs and development time. Expert systems with ability to understand circuit function and malfunction are not expected for at least 5 years.

ROBOTICS applications to factory production is a developing new field. There is little economic justification for near term use of robotics for low volume production or maintenance.

AUTOMATIC PROGRAMMING may have some use in test program generation, but this is unproven even for the commercial market.

PERCEPTION and pattern recognition for discrimination of false alarm and intermittents will be viable in 3 to 5 years. Dr. Pau's work shows the current capability.

COMBINATORIAL AND SCHEDULING PROBLEMS have no current application to testability. Needs in this area are already covered by other techniques (i.e. operations research).

VOICE SYNTHESIS AND RECOGNITION is very active but computer generated graphics should provide more benefits in the near term.

INTELLIGENT COMPUTER AIDED INSTRUCTION is being actively investigated by military training organizations. It provides no cost effective benefits to testability in the near term.

MACHINE LEARNING can provide a breakthrough in reducing development costs for some maintenance expert systems.

2.1 THEOREM PROVING

Our survey for this contract found no evidence to change the following statement by Boeing in the Integrated Testing and Maintenance Techniques (ITM(1)) final report:

"Theorem proving—this branch of AI attempts to produce programs that can use a given logical concept to prove new ones. This is not immediately applicable to the testing and maintenance field because the real world concepts and rules are not well defined and the input data is noisy. Current theorem proving systems using predicate calculus and propositional logic are not readily adaptable to this scenario. Future developments in the field of fuzzy logic may make theorem proving more applicable."

The Artificial Intelligence Applications to Maintenance Study (AIAM (3)) suggested possible applications of theorem proving, but no one has tried a practical application of this theoretical concept:

"BIT signals are too often false alarms. In addition, intermittent failures are difficult to distinguish from false alarms. Theorem proving techniques could be employed to test BIT signals to discriminate against false alarms and to identify intermittent failures."

2.2 NATURAL LANGUAGE PROCESSING

Natural language processing is the branch of AI that attempts to create machines with human-like communication skills. This field must borrow heavily from linguistics and other sciences to understand how humans communicate.

Natural language processing programs are usually used as an interface between a nontechnical system operator and a complex computer system. For example, a natural language interface could be used as an interface to an intelligent data retrieval system.

AIAM (3) stated:

"A medical diagnosis system, MYCIN, can carry on a conversation with a doctor about bacterial infections. It is certainly a near term possibility that a maintenance system can be made to converse with its user in a useful subset of English. This would be accomplished by the user typing in his side of the conversation. The machine could respond by printout, CRT display or synthesized speech."

"Spoken interaction would be highly desirable as it would free the maintenance man from the terminal. He could then have both hands free and could operate in remote locations using a portable headset to consult his computer."

The Personal Electronic Aid to Maintenance (25) is a portable unit with some speech input capability that addresses this last item. The NBS report "An Overview of Computer-Based Natural Language Processing" (NBSIR 83-2687) is an excellent 70 page summary of the issues, research required, forecast, etc.

Overall, while natural language processing can be considered a developing area, with potential for application to testability problems (i.e. speech input/response units), it has not matured enough for immediate application. Limited (if expensive) applicability is possible in 3 to 5 years as speech recognition units increase their vocabulary and reduce or eliminate their training requirement to adapt to a user's voice. Voice response units, while more mature still require substantial resources for random statement generation capability; voice quality is improving and is now well beyond the mechanical, monotone computer voice that has become a cliche of synthesized speech (see also section 2.9).

2.3 INTELLIGENT RETRIEVAL FROM DATA BASE

There are many testability applications that must retrieve information from a database. An intelligent retrieval speeds up the process and increases the amount of relevant data found. The ITM description was:

"Intelligent retrieval from data base—a means by which a maintenance crewmember can acquire a faster understanding of fault characteristics. The retrieval scheme might, for instance, contain a set of simple correlation pairs that are analyzed during postflight. These pairs might check a given type of fault against flight mode, acceleration, temperature, etc., and the system would notify the crewmember of any recognized correlations. Additionally, the system could contain more complex correlations such as, if conditions A, B, and C occur within 10 min, then fault X probably is causing the failures." (1)

AIAM (3) had a different application in mind:

"Inferential Retrieval from data bases: current applications to maintenance of this topic must be considered only on the fringes of AI, with the possible exception of automatic test pattern generation (ATPG). ATPG is used to generate the test patterns for digital logic. At present, this machine approach is superior to the human in formulating tests for combinatorial logic, and inferior in sequential logic.

Near term possibilities are the improvement of machine handling of sequential logic and development of ATPG for analog circuitry. The ultimate potential would be the complete elimination of the manual part of the process."

With over 40 organizations actually pursuing research in AI use with database systems (SIGART Oct. '83), we see this to be a very active topic. A few products are even available for the IBM-PC (e.g. R:Base, TK Solver). The goal of this work is to not only speed up the use of a database, but to find more relevant information for the problem at hand. Bibliographic databases, for example, typically retrieve less than 40% of the relevant material.

The systems are also gaining capability to retrieve related information by use of fuzzy set theory, special database machines, and by use of a special IC by Proximity Technology (Ft. Lauderdale, Florida) which can accurately find information even with misspellings and interchange of characters. Due to the large commercial market, progress is now being made quickly, and it is expected that some results in intelligent retrieval will be usable in testability problem solutions within the next five years; the capability of starting an application within three years appear promising.

2.4 EXPERT CONSULTING SYSTEMS

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Expert systems are probably the hottest topic in AI today. Expert systems have introduced a new way of preserving knowledge. Such a system is able to retrieve and process stored knowledge to perform such functions as diagnosis, monitoring, prediction, and planning. Currently, all operational expert systems are rule based; that is, the knowledge is stored in the form of if-then or situation-action rules. These rules (also called production rules) form a network of inferences that are used to perform the expert functions.

"It has become fashionable today to characterize any large, complex AI system that uses large bodies of domain knowledge as an expert system. Thus, nearly all AI applications to real-world problems can be considered in this category, though the designation 'knowledge-based systems' is more appropriate." (6)

An expert system consists of (6):

1) a knowledge base (or knowledge source) of domain facts and heuristics associated with the problem;

- 2) an inference procedure (or control structure) for utilizing the knowledge base in the solution of the problem
- 3) a working memory—"global data base"—for keeping track of the problem status, the input data for the particular problem, and the relevant history of what has thus far been done

Hundreds of articles have been written on expert systems, and over 20 of the most relevant ones are in the bibliography.

Teknowledge (a front runner of dozens of knowledge engineering companies) listed some situations that need knowledge engineering; often in the form of expert systems. These situations result from many testability problems:

- o The organization requires too many skilled people to recruit or retain
- o Problems arise that require too many possibilities to be considered
- o Job excellence requires a scope of knowledge exceeding reasonable demands on human training and continuing education
- o Problem solving requires several people because no single person has the needed expertise
- The company's inability to apply its existing knowledge effectively now causes management to work around basic problems

Teknowledge also listed attributes for selecting an appropriate application, many of which apply to testability applications:

o Primarily symbolic

- Commitment and availability of expert
- o Importance of the problem (who cares?)
- Scope of the problem
 - bounded domain
 - human solves problem in 3 hrs. to three weeks
 - vocabulary of basic concepts consists of a few hundred terms
- o General agreement among specialists about knowledge

- o Data and test cases available
- o Highly combinatorial problems are likely candidates
- o Incremental progress should be possible

Knowledge engineering is so new that only one book (by Teknowledge) has been written on the methods of building expert systems (36). With dozens of ways to make an expert system (table 2.4-1 from (6)), care must be taken in selecting the right tools for the tasks. Far too often this survey found people or organizations trying to use an AI language that happens to work on their machine to make an expert system for their perceived needs. Many aerospace contractors have realized this problem and, as a result, formed internal company AI centers for concentrating knowledge and tools. To minimize the need for knowledge engineers, IBM, Boeing and others are developing systems that are expert in eliciting knowledge about a domain from the user. This is one of several techniques that, when available, will make the building of maintenance expert systems more cost effective.

Maintenance Expert Systems

The maintenance uses of expert system have been well summarized by AIAM (3):

"Expert systems are in practical use today for configuring computer systems (R1) and are available for medical diagnosis (MYCIN, CADUCEUS) and locating mineral deposits (PROSPECTOR). There are also expert systems in various states of development for fault isolation. These include DELTA for the maintenance of locomotives, REACTOR for nuclear reactors, CRITTER for digital circuits, IDT used on a computer, and DART, designed for computer hardware. (See also position paper by Caren on a generic maintenance expert, LES). Hence, maintenance expert systems are relatively near term possibilities for applying to testability.

The diagnostic search programs (LOGMOD, STAMP, FIND), mentioned above, would seem to be a valuable adjunct to an expert maintenance program in that they can be used by the program to set up its strategy from the design of the unit under test.

An expert system requires a knowledge base of its domain. At present, this is provided by the user. LOGMOD, et al, require user layout of the system and user generation of appropriate tests. The ultimate expert system would use advances in automatic programming to perform fully automatic testing by deriving its knowledge from a machine-read schematic, forming its strategy from that knowledge, and generating appropriate tests as it needs them.

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C.A.I. Medicine x <	El.	Analysis	Elec. Circuits	×					×	×								
Vinowl. Acquis. Geology x	GUIDON	C.A.I.	Medicine			×												
ADRAL Learning Chemistry x	KAS	Knowl. Acquis.	Geology	×	_							_						
Concept Formation Math x	META-DENDRAL	Learning	Chemistry	×				×										_ :
Monitoring Medicine x	AM	Concept Formation	Math	×				×			_	_	_	_				:
Data Interpr. Chemistry x	ν	Monitoring	Medicine		-	×	×			\vdash	-		_					
Design Computers x	GAI	Data Interpr.	Chemistry	×				×					_					
Planning Robots x <	RI	Design	Computers	×			×								-			:
Planning Robots x <	ABSTRIPS	Planning	Robots		×											1		
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Design Elec. Circuits x x x x x x x x x x x x x x x x x x x	MOLGEN	Design	Genetics			J			×		×		_		-	1		1
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Data Interpr. Crystallography x	HARPY	Signal Interpr.	Speech Unders.	×		4					\dashv		×		_	j	1	
	CRYSALIS	Data Interpr.	Crystallography			×		×		-			_					/

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Control Structures of Some Well Known Expert Systems TABLE 2.4-1

Once the ATE has the knowledge it needs to operate as an expert system, it can also be used as a maintenance aid to direct a human when his intervention is necessary. It could also provide the interaction needed for training its operator. Thus, the expert system would serve as ATE, maintenance aid, and training device. While probably not a short term effort, the integration of maintenance aids should not be a far-out proposition. Integrating a training capability will be a long term proposition needing advances in computer aided instruction (CAI) techniques.

Computer aided design (CAD) programs can be considered a form of expert system, even though their current approaches may not be considered to be examples of AL. The Rome Air Development Center is studying the incorporation of ease-of-test considerations to CAD programs. From these can spring an expert system which will create a design with a minimum of maintenance problems. This will require the creation of a set of design rules for ease of maintenance and a set of rules to trade these off against other considerations such as thermal design, wiring constraints, etc. The design rules should be a near term possibility, but creating the trade-off rules will be a more difficult task."

The many maintenance expert systems surveyed were created by over a dozen different methods, only a few of which are generic and can be adapted to another system with little or no change in its rule structure (8, 9, 10, 11). However, Pau (11) has developed over 400 diagnostic metarules which appear to form an excellent structure for many maintenance expert systems. Dr. Pau uses a nested set of decision tables similar to failure modes and effects analysis (FMEA) to store the information (figure 2.4-1). The resulting diagnostic system architecture includes a learning database (figure 2.4-2).

Another approach to reducing the cost to generate and validate an expert system is to have it generate its own knowledge base from observations. Mitchie suggested that "most experts learn by example, so why shouldn't an expert system?". The machine learning approach is a breakthrough technique. It is discussed in section 2.11.

The third major improvement in effectiveness of a maintenance expert would come from expanding the current shallow knowledge of a unit under test to include deep knowledge. Kinnucan (28) provides a good survey of research in deep electronic knowledge:

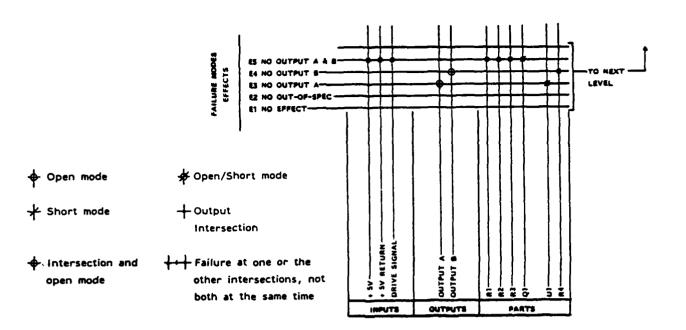


Figure 2.4-1 Decision Table

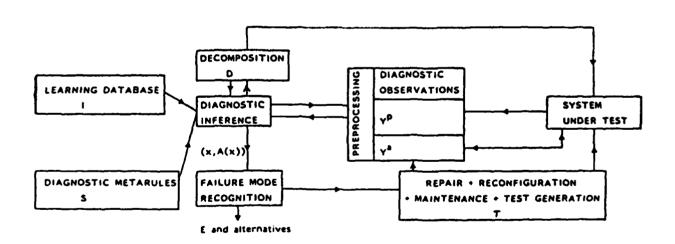


Figure 2.4-2 Diagnostic System Architecture

"A group headed by Randy Davis at MIT is developing an expert system for diagnosing electronic equipment, a system based on knowledge of the structure, function, and behavior of circuits. This system will represent both the physical and functional structure of the systematic.

These systems work by pathways of causation. Representation of both physical and functional structure of the system is necessary because functionally adjacent components may be physically separated. For example, the circuits that make up a single subsystem may be physically separated on a printed circuit board. Yet two physically adjacent circuits may belong to quite different functional units. Physical representation allows the system to detect faults such as a solder bridge between two pins of an integrated circuit, as well as those that can be logically traced through functional linkages.

The system models devices by treating them as black boxes with input and output ports that are in turn connected to other devices. The normal function of the device is represented by simulation rules that specify an output for a given input, and inference rules that state what can be inferred about the inputs of the device from the values of its outputs, assuming the device is functioning normally. This representation is hierarchical. Each of the major components of a system can be broken down into smaller parts. This allows the expert system to deal with the enormous complexity of computers and other electronics systems (although a complete model of even a modest size computer is not going to be predicted in the near future).

It makes diagnoses by a procedure Davis calls 'discrepancy detection'. The system simulates the behavior of a suspect device to establish its normal outputs. It then compares the device's actual output with the simulated output. If there is a discrepancy, the component is known to be faulty."

In interviews with both Davis (27) and Generseth (28), they concluded that this work is not expected to be useful for field applications for at least 5 years. When it does become practical, an electronic maintenance expert system will need on-site real-time computation capability, which implies use of at least the capability of an engineering workstation or special purpose AI machine (sec 5.11).

2.5 ROBOTICS

At this time robotics is being used in testability application research to place boards on testers and for guided probe placement. It is being enhanced by vision and other sensory applications such as the ability to "feel" pressure. This application is so new that bugs and reliability problems still exist in demonstration units.

Use of robotics is not economically feasible for factory, organizational level and most depot level military testability applications for at least five years, as the current state of robotics requires very predictable, high volume operation for economic use.

2.6 AUTOMATIC PROGRAMMING

Our survey shows that automatic programming has been used to analyze the structure of a program and in determining how the resulting analysis can be used to guide a proof of correctness for that program. More recent research shows that automatic programming approaches have been used for program synthesis. With the results from this research, the discipline may have an application to testability. However, because of the scarcity of information in this area and the lack of specific research applicable to testability, automatic programming is judged to be more than five years away.

"ATPG can be considered an example of automatic programming. There are also programs which assist a test engineer in creating ATLAS statements for test equipment. Though these are not really sophisticated enough to warrant the title. The ultimate application of automatic programming will be the real time generation of ATLAS test vectors from a computerized representation of the system, as they are needed by an expert system isolating a failure. This is definitely not a short term goal." (3)

Much work in automatic programming is needed for it to be applicable to the highly controlled software environment of the military.

2.7 PERCEPTION PROBLEMS

The most advanced use of perception is shown in several of Dr. Pau's papers (11, 12, 13, 14, 15). In "Integrated Testing and Algorithms for Visual Inspection of Integrated Circuits" (12), he combines electrical testing with visual image analysis before the lid is put on the IC. This test expert system could be extended to PC board inspection by computer using visible or infra-red light combined with electrical testing for fault diagnosis.

In Pau (14) "Application of Pattern Recognition to Failure Detection and Analyses in Non-Digital Systems," perception techniques are discussed that could be applied to detect degradation of mechanical parts (engine, etc.) before they are destroyed by bearing failure, excessive vibration, etc.

CR Technology (1701 Reynolds, Irvine, California) has a pattern recognition system that connects to ATE to read 6 lines of characters with a television camera, listen to tones and manipulate switches. This system is expected to have complete (or extended) pattern recognition capability to "read" the fully electronic dials of new aircraft. This is the first example of a product with embedded AI that can be used in the situation test. But while it eliminates the technician's need to confirm displays, it does not produce the large scale cost savings desired by this study.

However, an additional driver is that in order to discriminate false alarms from intermittents, pattern perception techniques must be developed to process the data that will be available in 3 to 5 years from Smart BIT.

2.8 COMBINATORIAL AND SCHEDULING PROBLEMS

Combinational techniques can be used in finding the optimal path in a network. In testability these could theoretically be used in obtaining the least time or least cost path to finding faults using a large ATE program. No references to application of these techniques with any relevance to testability were found.

Scheduling problems have historically been solved best using operations research techniques; they can also be solved through use of AI. Scheduling techniques could be used in the near term to develop models to analyze maintenance queueing for minimum impact on system down time. But with the assortment of mature non-AI techniques now used to accomplish these types of tasks, AI scheduling is probably not of economic interest for testability.

2.9 VOICE SYNTHESIS AND RECOGNITION

Voice synthesis is now a tool being applied to commercial systems for restricted vocabulary voice output from computer. Voice recognition, even with heavy R&D

funding, is not yet an easily applied tool. The Japanese are expected to be front runners in voice recognition with their 5th generation computing project and only 500 syllables in their language that need to be recognized.

Voice Response (synthesis)

On some ATE (Fairchild series 70), voice synthesis allows the operator to keep his eyes on the unit under test while performing diagnostics. The Texas Instruments Professional Computer has one of the best synthesis systems for personal computers. There are many synthesis techniques used to electronically generate the 40 English phonemes.

Voice Recognition

With 10,000 syllables and 100,000 English words that need to be recognized, automatic dictation is not expected until the 1990's. "Widespread use of voice recognizers await the availability of low cost connected speech systems achieving better than 99% accuracy with limited vocabularies—100 words." (6) There are indications that a speech understanding system using a Natural Language parser will be introduced by IBM in the mid 80's. (6). CAD/CAM systems are also now becoming available with voice input for the control applications, leaving the hands free to use a graphics tablet, light pen or mouse.

In the future, voice input might be a more efficient way for a user to provide information to the ATE; however, the current graphics menu input system, with mouse, track ball, etc., may be as fast and is a proven low risk technology. While data compression techniques have allowed voice synthesis to be done on special IC's, even 100 word recognition still requires a fast, powerful computer, and training is required for a system to understand a speaker's natural voice variations and moods. The Personal Electronic Aid for Maintenance project at TI (25) will have some speech recognition capability and its progress is worth following. Speech recognition is a high risk, high cost AI technique for the next three to five years.

2.10 INTELLIGENT COMPUTER AIDED INSTRUCTION

Al techniques are being used to improve the quality of computer aided instruction (CAI). The Al version of CAI is usually called Intelligent Computer Aided Instruction (ICAI). It differs from traditional CAI in that the deterministic programming of the order of presentation of material is replaced with AI techniques. Thus the system has the capability to better adapt to the student's individual needs; whole sections of instructions may be skipped (or emphasized) by the AI program's assessment of the student's progress.

ICAI systems consist of: (1) problem-solving expertise, which is the knowledge the system tries to impart to the student; (2) the student model, which monitors what the student does and does not know; and (3) tutoring strategies, which specify how the system presents material to the student.

Our investigation in this area shows that the application of AI techniques to CAI will not have a significant effect on testability quality or provide a cost savings in the near term.

In fact, current research has failed to show any significant improvement on the learning curve of the student by use of CAI or ICAI. The use of video disks may give CAI a wider range of teaching techniques, but the techniques used by a good teacher have yet to be encoded into a computer (40). A new journal, Machine-Mediated Learning, contains many items on ICAI. Intelligent Tutoring Systems (41) is a good overview book. Further references are found in the maintenance training part of section 8.2.

Richardson (5) reviews 12 Intelligent CAI systems and concludes that, while no robust system now exists for military use, more effort in the area will produce usable results. The time frame for practical application in the military is at least 3 years off, probably 5 years or more.

2.11 MACHINE LEARNING (Decision Tree Induction)

Machine learning is an active area in artificial intelligence which combines several AI techniques: expert systems, intelligent retrieval from databases, and pattern recognition.

Machine learning systems have been developed and applied to a wide variety of diagnostic problems (17, 19, 20). Machine learning is defined as constructing an organized representation of experience by a computer. The possible types of machine learning include:

- o learning by being constructed or programmed (rote)
- o learning from instruction (by being told)
- o learning by deduction
- o learning by analogy

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- o learning from examples
- o learning form observation and discovery

It is widely recognized that automatic learning using artificial intelligence techniques within an unstructured domain is a very difficult task and that little in the way of practical application has been demonstrated. However, when the task domain is restricted to that of learning from observation of data presented in tabular form, it has been shown to be a practical technique. To be usable, the table must have all relevant attributes for the diagnostic decisions. The expert does not have to tell the relevance of each attribute, but every attribute which might have some relevance, even if it is not used consciously in his diagnostic decision, must be included. As is true with human learning from observation, both positive and negative examples of diagnostic decisions must be included in the tables. Testability applications of machine learning could use observation of the diagnostics performed by an expert to infer the rules that he used.

Machine learning appears to have the most potential for the military testability situation by being applied to fault diagnosis. The following are some of the attributes that would have to be in a data base in tabular form for machine learning to perform fault diagnoses for electronic equipment:

- o Field fault information
- Tester data (not just GO/NOGO results)
- o Test results from other relevant test steps
- o Functional signal dependency table

- o Results of repair (did the repair cure the problem)
- o Fault history of unit
- o Diagnostic decisions by technicians
- o Intermittent failures (SMART BIT generally needed to obtain this fault data)

Dr. Michalski's work at the University of Illinois has produced a machine learning system which forms a knowledge engineer's workbench for tabular data. His Intelligence Systems Company of Urbana, Illinois, is marketing an "Assistant for Building Better Expert Systems" (ABBESS), which determines attribute weighting by use of a variable valued logic system. Each attribute should have less than 20 values for efficient learning with ABBESS; this is adequate to describe the attributes for electronic diagnosis. Instead of merely recording if a test step passed or failed, the following nine catagories of test result could be recorded:

- o Passed test
- o Passed test but noisy
- o Passed test but oscillation present
- o Passed test low (or high)
- o Failed test but almost passed (low or high)
- o Failed test low no signal
- o Failed test low noise
- o Failed test high distorted signal
- o Passed test signal distortion

The diagnostic and test attributes described above provide the learning program with sufficient information to automatically determine the significant attributes of the mangenerated diagnostics.

Michalski (18) compared machine learning using a program similar to ABBESS with 18 other numerical taxonomies for two classification applications — selection of micro-computers and diagnosing soybean diseases. Machine learning appears to have capability for building expert systems in less than 1/10 the time required for standard rule-based techniques, while generating more precise production systems than those obtained from

experts. This suggests that machine learning by observation could provide a better tool for diagnostic analysis than those previously used.

Michalski's publication on diagnosis of soybean disease provides us with a concise example of machine learning of the diagnosis process used by humans. The soybean disease diagnosis involves the use of training data from a soybean expert. The structure of the soybean application applies to electronic diagnosis and improvement of Automatic Test Program Generation, even if the content of the tabular data does not. The soybean expert was trying to classify 15 diseases by analysis of 35 multivalued attributes, some of which were:

- o Time, rain, temperature, hail
- o Number of years crop repeated in same location
- o Damaged area of plant, plant height
- o Leaf spots and spot size, mildew or seed mold and seed size

The machine learning system could correctly diagnose a disease after using only 290 training examples. This was compared to another expert system using rules extracted from a botany expert. Comparison between the two systems follows:

	•	One of	
	First Choice	Two Choices	Not
Туре	Correct	Correct	Diagnosed
Machine learning	98%	100%	0%
Expert system	72%	97%	2%

Both the machine learning and the conventional expert system were forced to limit diagnosis to 2 choices, and order them by priority. The rule based expert system had the correct diagnosis as the first choice 72% of the time and had the correct diagnosis as one of the two choices 97% of the time. It failed to make any diagnosis in 2% of the cases. ABBESS produced much better results, always making a diagnosis. In more complex learning of diagnoses ABBESS has used up to 100,000 examples to develop crisp rules.

This very large data base is far beyond human capacity to fully understand or translate into an expert system.

ABBESS illustrates that it is not essential to use a regular AI language (e.g., LISP) or machine (e.g., Symbolics, Dolphin, LMI). The ABBESS system is implemented on a DEC VAX computer using 30,000 lines of Pascal code. This Pascal code is able to perform many of the functions of LISP, the preferred artificial intelligence language. The resulting production rules (diagnostic decision tree) can be run on a much smaller Pascal based machine. Currently, an IBM PC is used for rule execution after learning is complete.

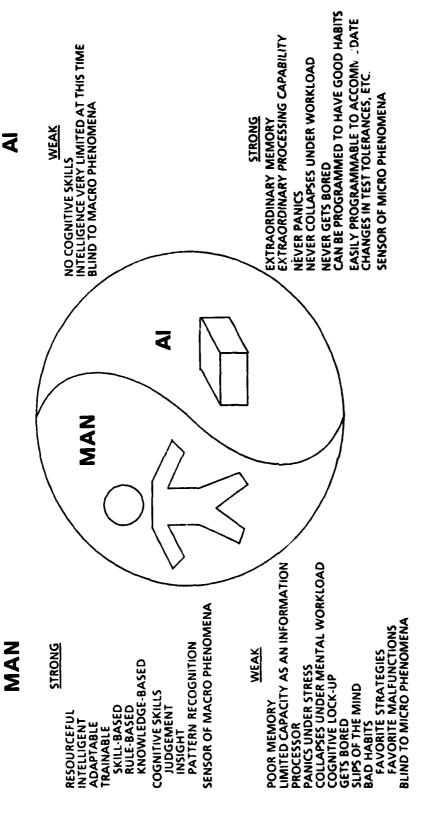
Another machine learning program, from England, has less capability than At. 3ESS; however, it runs entirely on an IBM PC using a spread sheet type of data entry. Expert Ease was briefly reviewed (Datalink, June 27, 1983) and is available from Export Software International 4 Canongate Venture. New Street, Royal Mile, Edinburough, Scotland EH8, 8BH.

2.12 CONCLUSIONS

Computer systems now have sufficient computational capacity that can be used to understand and help the user, rather than just obey some precisely formulated commands. Artificial intelligence provides a set of techniques for allowing the person and computer to work as a team. with each member of the team having special capabilities (figure 2.12-1) (31).

Expert systems is the most active development in artificial intelligence, and is now capable of being used with several testability applications as a knowledge manager. An expert system could be used to:

- Get knowledge into a computer
- o Test it
- o Debug it
- o Fill gaps



THE WEAKNESSES OF ONE ARE COMPENSATED FOR BY THE STRENGTHS OF THE OTHER

From: Integrated Diagnostics Feb 84

FIGURE 2.12-1 Man and AI Can Work Together Harmoniously

o Extend it

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- o Modify it, and finally
- o Give the knowledge back to the human in improved form

Diagnostic metarules and machine learning will allow maintenance expert system tools to be developed which can be easily applied to many projects. Presently most expert systems are developed through the knowledge engineering lifecycle (figure 2.12-2) for each project with the knowledge coming from a single human expert. Maintenance expert system tools have been created (8, 9), including some which can incorporate diagnostic experience (10, 11). The use of system independent diagnostic metarules will permit a maintenance expert system to be created without the extensive refining, redesigning, reformatting feedback shown in figure 2.12-2. These techniques should reduce the time to create an expert system for maintenance from five manyears to one manyear for commercial systems. By using extensive validation and verification of metarules, allowing the users to modify the data only, and by having internal rules for data consistency checking, maintenance expert system tools should be able to be developed for military applications.

During the next three years no new AI developments in understanding circuit functions and faults through "deep knowledge" is expected. It may, however, be possible that AI can be teamed with a system that already understands circuit

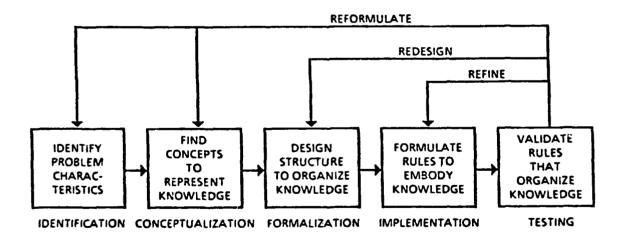


Figure 2.12-2 Knowledge Engineering Lifecycle

functions (i.e., the engineering work station). This combination would be able to simulate circuit operation and faults while a unit is being diagnosed. without requiring the ten to fifty manyears of development if done by AI alone.

The summary of the status of AI techniques for application to military testability is shown in table 2.12-1. Although some techniques are useful to military testability, most would not yield significant cost benefits in the near term, if ever. This topic in the form of life cycle cost benefits of potential AI applications, will be discussed later in the study.

	Tool can		Substantial		
	be used	Research	progress		
	now	activity	in 2-5 years	Useful	Required
Theorem Proving					
Natural Language	*	**	*	*	
Processing					
Intelligent Retrieval	*	**	*	*	*
from Data Base					
Expert Consulting System	**	**	*	**	*
Robotics				*	
Automatic Programming		*	*	*	*
Perception				*	
Combination and			*	**	
Scheduling Problems					
Voice Recognition	*		*	*	
Voice Synthesis		*		*	
Intelligent Computer		*		**	
Aided Instruction					
Machine Learning	*	* *	*	*	

Table 2.12-1. AI Technique Status for Military Testability Applications

3.0 SURVEY OF EXISTING AND DEVELOPING BIT AND ATE

The two primary methods of testing military electronics, Built-In Test (BIT) and Automatic Test Equipment (ATE), have reached limits of capability that still require excessive manpower for maintenance. A survey was made of BIT and ATE problems and the potential for near term application of artificial intelligence. Information was obtained from published literature and reports, interviews with ATE vendors, and relevant R&D groups in government, industry and universities.

The key BIT/ATE findings show a lack of uniform application of Design for Testability (DFT) techniques:

- o Present application of AI to BIT and ATE is practically nonexistent
- o Designers not given incentive or feedback on DFT for BIT/ATE
- o Inadequate management perception of DFT quality
- o ATE problems generally due to lack of adequate DFT and BIT
- o ATE test problems increased because BIT data is often ignored
- o BIT experts needed since BIT is frequently designed new for each military acquisition

Military BIT and ATE, as applied now, are expensive to implement. Neither one is specifically supported by automated design tools, although general CAD tools are applicable. This survey revealed opportunities for artificial intelligence to provide improvements to both BIT and ATE, especially where it supported DFT decisions made in the early phases of a project concerning tradeoffs between BIT and ATE.

The designer frequently is not aware of the burden that a lack of BIT (or insufficient BIT) or other DFT shortcomings places on the ATE or the maintenance technician. Since the designer frequently has no means to measure how well BIT or ATE will do his job, there is no feedback to gain the expertise that improves designs.

There has been a tendency to ignore testing of complex electronics as a design factor during early phases of a project. This results in much more complexity in the ATE which, in turn, becomes very costly because it must bear all of the test impact. By inserting better testability through BIT into the early design phases, the portion of life cycle costs due to testing can be reduced.

3.1 BUILT-IN TEST (BIT)

The use of BIT is increasing but the application results have been poor due to nonuniform methods and lack of verification techniques. As a result, operators and technicians have no faith in BIT with its high rate of alarms which cannot be traced to a cause.

The BIT considerations in Table 3.1-1 (31) show that either a BIT design expert is needed to make the right BIT the first time, or else the design must evolve. Unfortunately, a program's time constraints frequently do not permit much design evolution.

3.1.1 BIT Trends

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Military BIT experiences excessive false alarm rates, caused by incorrect BIT design and intermittent and transient faults due to effects which were not (or could not) be considered during design. There is work in progress to reduce the rate of false alarms by:

- o Developing new false alarm filters (Malcolm 46)
- o Providing better built-in test trades at the early phase of design, and providing for testability data collection, analysis and corrective action, (MIL STD XXXX, (21) RADC Testability Notebook (22))
- o Recording field built-in test results for maintenance use (1)
- o Developing a SMART BIT to incorporate false alarm filters, fault recording, etc. (RADC Contract, F30602-84-C-0051, in work)

This survey found no work in progress on simulating intermittents and other false alarm conditions during the design phase.

The following factors all tend to reduce the amount of BIT implemented in military designs, thus pushing the burden of test on the ATE:

- o Lack of expert BIT designers
- o High cost of reinventing BIT for each program (no BIT standardization)
- o Lack of management visibility tools to help judge quality of BIT design
- o Support organizations have minimal involvement in weapons procurement

Commercial incorporation of BIT designs for computers, self-checking integrated circuits, and VLSI self test have proven that it is cost effective to incorporate BIT capability when a complex product is being marketed for high volume applications. The opportunity now

Lack of scientific basis (inadequate utilization of existing knowledge) Decision theory (maximize expected value)

Bayesian analysis (explains why testability problems are inherent in high-Maintenance decisions are made by people, not machines reliability systems) Games theory (optimal strategies)

Statistics (testing should accommodate randomness of system performance, due to random stresses)

2. Lack of understanding of subtle failure modes

Incipient failures "Failure without a fault" Interconnection faults Interface problems Soft failures

Difficulty in predicting how fault-free systems will function under field conditions m

Real world performance may be quite different from anticipated—unexpected stresses/power forms/stray interference/ inadequate cooling, etc

To counteract, BIT requires maturation period

Reconciliation between specification requirements and user needs in real world Designers design specification User needs may differ from spec requirements

Difficulty in coping with "rare" failure event

Lack of familiarity creates maintenance inefficiency "Once in a life time" failures may require that unit be returned to vendor for diagnosis

designs are consciously tailored to majority problem: minority ignored Intermittent faults ignored Multiple faults ignored 듈 ف

Lack of appreciation of diagnostic procedures taxonomy ۲.

Knowledge-based Rule-based

Lack of appreciation of psychological factors
Human perormance under stress
Decision-making under varying conditions (war/peace)

9. Management maintenance policies

Policies may defeat efficient maintenance procedures Typically, pressure is to keep systems flying at all costs No time for thinking or deductive processes No time for developing skills

Lack of utilization of human talents Judgement ability - There are situations where BIT should be ignored ö

Interpretation ability - Skilled maintenance people have remarkable insight

Lack of utilization of available resources =

Historical data from previous flights not utilized Historical data from maintenance data collection systems not used Experience data from other squadrons/bases not used

Lack of resources applied to solving BIT problem When funding gets tight, BIT design efforts get shelved

Use acceptance of work-around solutions may result in the designer not finding out about the problem (the problem never gets solved) 13. Willingness on the part of the user to accept BIT deficiencies

Lack of coherent approach in system design BIT designed independent of prime equipment design (instead of as an integral part) ₹.

15. Lack of system approach in integrating various maintenance levels
O-leve///leve///Depot designed as separate entities

16. Lack of flexibility in BIT design

BiT should be designed to accommodate varying conditions Varying tactical conditions Varying requirements for mission Ground versus flight

Varying urgency to perform missions Varying logistics capability BIT should be designed for varying users – Pilot/Radar operator/Maintainer

17. Antagonism against any form of maintenance aids at organization level Hand-held computers, suitcase testers, etc. have a place Totally different scale than old-style "Yellow Gear" equipment

18. BIT not very friendly to user Interactive capability not fully exploited

€

Human nature BIT may prescribe an orderly diagnostic procedure (remove unit 1, then 2) Maintainer will do what is easiest (remove unit 2 first)

Generic Issues in Designing Bit Table 3.1-1.

exists to develop standardized BIT approaches which can be used in many military applications and standard verification techniques to validate them (RADC Contract: BIT Verification Techniques F30602-84-C-0021 in work).

3.1.2 AI Applications to BIT

Development of standard BIT functions that could be implemented in a general purpose BIT module would be of significant benefit to the military. A weapons program should not expect to create a generic BIT within its program schedule, just as it does not expect to develop a new microprocessor for a program. To be practical, the BIT must easily adapt to applications, conditions, and the users' requirements. It must also capture information from hard and intermittent faults which can be used as an aid in subsequent diagnosis. Such a BIT design, which has had extensive verification and validation for the military environment, would permit a low cost, high quality BIT to be used on many programs.

The same forces which have resulted in highly sophisticated, high density electronics now permit creation of a highly sophisticated, high density BIT. Integrated circuit technology provides the opportunity to design a BIT element which can adapt to many future program needs. Technology trends toward denser circuit packaging and larger die sizes also support this approach.

Initially, the development of a BIT chip set (or IC, in its 2nd generation), which incorporates good false alarm filtering and has been extensively verified and validated for the military environment would provide a very low cost BIT solution for many programs. A BIT chip set would require minimal board area while allowing a proven design to be incorporated at low risk. Project offices generally require new programs to have BIT detection and isolation in excess of 95%, with a false alarm rate of less than 5%. These goals are difficult to achieve if BIT is designed concurrently with the rest of the program. An available standard BIT IC or chip set would make it easier to meet those requirements. This chip set should permit not only data recording and programmability but also support use of AI features. The RADC Smart BIT development effort which will attempt to use AI techniques may lead to such a capability (See section 5.4 for a description).

3.2 ATE SURVEY

The results of the ATE portion of the survey are summarized in figure 3.2-1, which relates BIT and ATE problem causes to their impact on test creation, test execution, and test maintenance. This section describes the problem areas and their causes, and then discuss the merits of curing a cause versus providing symptom relief. The conclusion of this section describes general solutions that will be discussed in more detail and applied to specific applications in Section 5.0.

3.2.1 ATE Problem Areas

Problems in ATE affect cost and capability in the creation, use, and maintenance of the test program set (TPS) which includes both the test software and the interface adapter. Kunert (42) provides a brief review of "ATE Applications of Artificial Intelligence" with suggested use of expert systems for:

- o System fault isolation
- o CAD with testability constraints
- o Fault diagnosis of a Unit Under Test (UUT) at the depot

3.2.1.1 Test Program Set Creation Problems

Test program cost and capability are a function of testability. As the number of gates to be tested increases, the relative cost for test generation increases exponentially when design for testability is ignored (See figure 3.2-2). Figure 3.2-3 shows that the number of tests needed to achieve a given test coverage level is also a strong function of testability. Devices may not be fully tested due to cost or creation time limitations. Test program sets are also very expensive to create when automatic test program generation or other tools are not available, as is frequently the case for the military ATE.

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Opportunities for Improvement		sbrishnete feeT	\times						X	
	Artificial Intelligence	Smart SIT							X	
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0	¥	Computer Aided Preliminary Design for Testing	X	X					X	
		Test Maintenance	TPS change impact unclear				Lack of rules and tools result in expensive SPR	SPR too costly way to add diagnostics		
ATE Impact		Test Execution	Excessive test time	Excessive test time	CND, RTOK persist	CND, RTOK persist and reinvent diagnostics	Must learn pecularities of each Test Program	Diagnostic experience leaves with technician	Good boxes tested unnecessarily	Unable to isolate on ATE
		Test Creation	Long complex test	Long complex test			Costly development, verification and validation required			
Causes		Design for Test inadequately considered by design	BIT inadequately considered by design	BIT not matured with use	Intermittant fault information not available	ATE hardware and software not standard, resulting in small market for support tools	Diagnostics not cost effective to incorporate on ATE	System testing has inadequate fault isolation	Static ATE tests frequently do not detect dynamic failures	

FIGURE 3.2-1 AI Opportunities to Solve BIT/ATE Problems

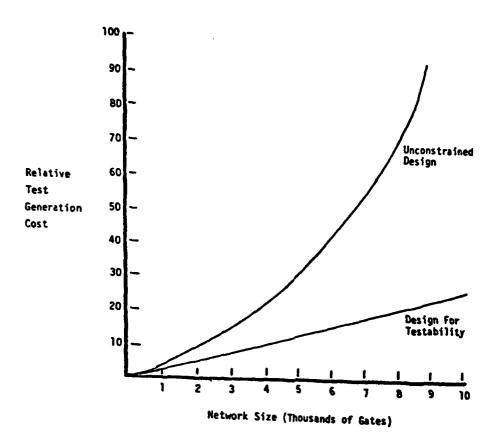


Figure 3.2-2 Cost Advantage of Design for Testability (Muchldorf IEEE TC Jan. 1980)

3.2.1.2 Test Program Set Usage Problems

Problems in using test programs on ATE include slow, sequential execution of end-to-end test, retest OK, and diagnostic knowledge which is slowly acquired by performing tests for many months then lost when diagnostic expert has left (tour of duty ended).

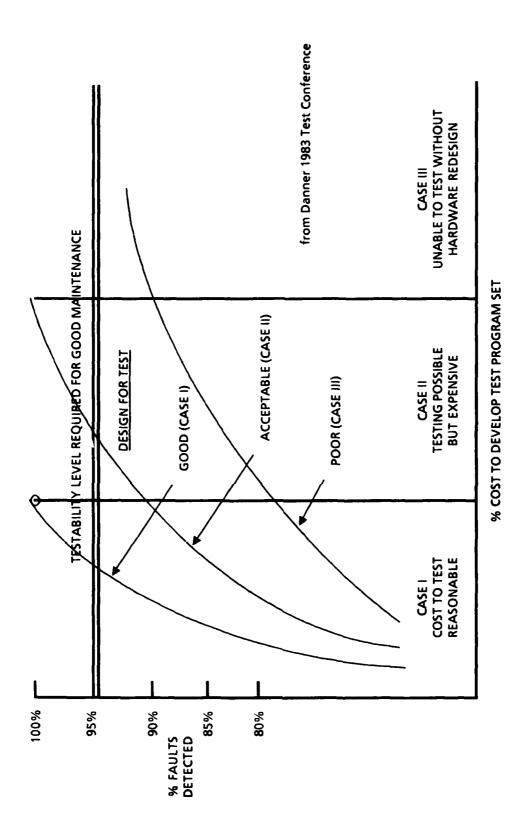


Figure 3.2-3 Fault Detection Dependence on Testability

3.2.1.3 Test Program Set Maintenance Problems

The TPS must be maintained to incorporate changes in units, support software (such as ATLAS compiler), ATE configuration, and diagnostics. General improvements in TPS coverage or diagnostic capability are frequently not incorporated; due to the extreme cost of military changes, there is a tendency to incorporate only those change requests which stop good units from failing tests.

3.2.2 Causes of ATE Problems

The major causes of ATE problems are the lack of design for testability features in the units being tested and the inadequate ability of management to measure DFT quality.

The lack of ATE speed or number of steps that can be executed without stopping (program depth) are less important problem causes and are also a secondary effect of the lack of DFT features in the unit under test. There is currently no incentive for the contractor to design a more testable product, since the contract is awarded to the lowest bidder and specific testability requirements are not part of the contract. It is also difficult to get management to know how well testability insertion is being incorporated, as the testability audits frequently have little relationship to subsequent field false alarm problems, quality of ATE diagnostic ability, etc. Rather than having the ATE "work harder" by increasing test speed to decrease execution time, the electronics designers should "work smarter" ensuring better BIT so as to reduce the number of box removals and make the ATE diagnosis tasks simpler. The economic leverage of eliminating a one month trip through the maintenance pipeline is much greater than reducing the length of a test from two hours to one hour.

3.2.3 Symptomatic Cures

The following techniques were found practical to provide symptom relief for problems that impact ATE through more cost effective generation of the test program set:

- o Improve Automatic Test Program Generation for complex circuits
- o Develop Knowledge Based TPS Assistant (Freund 43)
- o Develop an AI Assistant for Test Program Set Verification and Validation

However, the evaluation portion of this study (see Section 6.1.1, Life Cycle Cost Evaluation Criteria) found that reducing the problem cause is more cost effective than trying to provide symptom relief at each development phase.

3.2.4 ATE Problem Solutions

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ATE problem solutions involve both enforcement of testability standards and the use of AI. The proposed military standard on testability (21) will make the contractors aware of test needs by requiring them to do specific planning, tasks, audits, etc. However care must also be taken to balance additional administrative overhead in a program with good design practice. AI provides a means to create tools to be used by industry for testability insertion BIT design, and maintenance expert design. It will give the designer leverage in his attempt to "design smarter." These ideas are expanded in the AI applications presented in Section 5.0.

4.0 SURVEY OF TESTABILITY APPLICATIONS

This survey focused on those applications of artificial intelligence that have the potential of leading to quick payoffs and practical use. Six testability improvement areas were found to have a potential for near term application with, or as part of an AI approach. These six testability areas are summarized in this section.

1) Self improving diagnostics:

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- o Functional test sequences can be cost effectively improved
- o Incorporation of diagnostic experience through automated learning is a promising near-term concept
- o AI cannot improve observability of tested element
- 2) More effective fault detection and isolation:
 - o Better Design For Testability is the most cost effective means
 - o Smart BIT provides the only means to capture fault data in the field
- 3) Discrimination between false alarms and intermittent faults:
 - This capability will take at least five years to evolve. Information necessary is not captured and AI analysis techniques are not yet developed.
- 4) Reduction of skills required for maintenance:
 - o Al applied to information processing can reduce specific experience needed by a maintenance technician
 - o Computer Aided Instruction has not been proven to significantly improve learning
- 5) Integrated Diagnostics:
 - o AI can provide cost effective information processing for system, ATE, and bench testing
- 6) Design For Testability:
 - Testability expert (human or machine) is needed during the design process

4.1 SELF IMPROVING DIAGNOSTICS

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Fault diagnosis consists of three phases—fault detection, fault verification and fault isolation. The criteria for a self improving diagnostic (SID) system are as follows:

- o The system must be able to detect a fault, verify if it is a hard fault, (not a false alarm or intermittent) and isolate the fault to the replaceable component.
- o It must recommend and remember a fix.
- o After the recommended fix is made, it must determine correctness.
- o If the recommended fix is correct, then the information is saved. If the fix is not correct then the system must try a new fault isolation strategy. When the correct fix is found for the fault, this fix is saved, and the fault isolation strategy is updated.

4.1.1 Step One: Adapt Functional Test Sequences

Frequently a military ATE test will consist of a fixed sequence of tests. The first form of improvement is to allow the functional test sequence to adapt to field testing experience. Simpson (29) has proven its capability to learn the cost, time and MTBF associated with test steps and incorporate this knowledge into optimal modification of the test sequence. The knowledge gained by Simpson's System Testability and Maintenance Program (STAMP) (29) observation of field testing allows it to test earlier in the test process, those portions of a unit which fail more frequently, thus decreasing average testing time. STAMP also has the capability to optimize its test sequences for either peacetime conditions (low cost), or war (quick response).

4.1.2 Step Two: Incorporate Diagnostic Experience through Automated Learning (IDEAL)

The concept of IDEAL, proposed by this study, is to capture enough diagnostic information from the field to allow its automatic assimilation by a central processor. The diagnostic concepts come solely from the technician, and the program has no capability to reason about the circuit function. IDEAL is similar to the "The 'Experience Algorithm' in Automating Isolation of Single and Multiple Faults," (8.2 - Maintenance Expert), in which

Arington defines experience as the accumulation of knowledge and skill through action. He states that "experience programs are not meant to replace or even reduce fault isolation algorithms or the need for testability, but they can enhance and complement them technically and economically."

IDEAL allows the actions taken by expert technicians to provide guidance for all technicians. Pau (sec. 2.4) shows a tabular structure for describing circuits similar to Failure Modes and Effects Analysis (FMEA). This type of structure would permit implementation of IDEAL. Both IDEAL and the "Experience Algorithm" are concepts which have not been implemented, whereas Dr. Pau's work has. The IDEAL concept is discussed in Section 5.8 and is worth pursuing in more detail for its potential benefit in a three to five year time period.

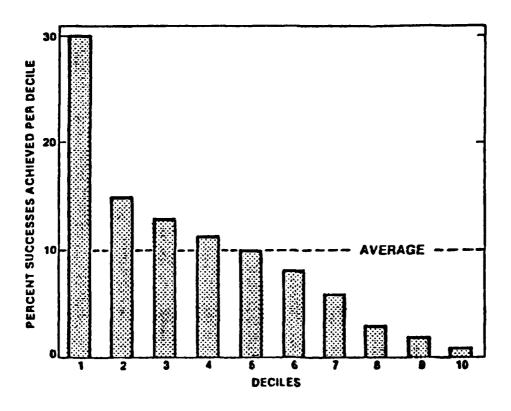
4.1.3 Benefits of Self Improving Diagnostics

There can be considerable savings in maintenance time by incorporating the field diagnostic knowledge. One of the reasons for the continuing high cost of fault detection/isolation is that real symptoms are frequently not identified in test procedures. The benefit of adapting test sequences and IDEAL is a decrease in the average maintenance time (functional plus diagnostic test time) for all personnel.

However, figure 4.1-1 shows that the experts which make up the top 10% (Decile #1) of the workers are correct three times as often as the average worker. If an expert system could be used by everyone that had one half the performance of the top experts, then the average shown in the figure would increase by 50%.

4.1.4 Status

Naval Electronic Systems is funding the only known work in self improving diagnostics. Harris Corporation is under contract to develop integrated diagnostics for a portion of the Tomahawk Launch Control system. During 1984 the "A" specification will be developed, and 1985 will see the development of hardware and software for automatic and semi-automatic diagnosis. This one-half million dollar contract will use self improving diagnostic concepts to develop a historical database of past failures and their proper solutions. The data will be searched before exhaustive tests are made on faulty boxes.



From "AI in the Airland Battle", <u>Astronautics and Aeronautics</u> July/Aug 83
Figure 4-1-1 Distribution of Expertise

This should reduce the test time, and perhaps eliminate the need for a maintenance manual. However, we do not expect results of this demonstration to be available for general use for several years.

4.1.5 Limitations of Self Improving Diagnostics

The diagnostics capability will depend upon the testability of the unit being diagnosed. If design for testability (DFT) has been ignored then fault isolation will be limited by the quality of the implemented DFT; SID related improvement may be small. DFT will also limit improvements in fault detection and isolation.

4.2 MORE EFFECTIVE FAULT DETECTION AND ISOLATION

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The Operations Reliability/Maintainability Engineering Study conducted for the Army (39) identified three reasons for the continuing high cost of fault detection/isolation that could be reduced by an improved BIT capability.

- 1. The cause of approximately 33% of all symptoms was found in an aircraft system other than the one in which the symptom was observed.
- 2. Approximately 50% of all symptoms observed via aircraft instruments and warning devices indicated a failure of the instrument or warning device rather than a failure of the monitored system.
- 3. Approximately 66% of all symptoms were not found in the system trouble-shooting tables. In only 50% of the other cases, was the most frequently reported cause of a symptom listed among the possible causes in the technical manuals.

Development of more effective fault detection and isolation techniques could, on the surface, help reduce the impact of three major testability problem areas: lack of design for testability (DFT), inadequate test procedures and inadequate test equipment. These are not totally independent problems, however. Resolution of those problem areas will, for example, likely involve recommendations for use of specific DFT approaches that in turn aid test procedures and simplify test equipment requirements. It has been show that the complexity of military electronics must be lowered to achieve reduction in repair time (7).

One typical problem in fault detection and isolation is the localization of faults in the conformally coated printed circuit cards commonly used in avionics. Most techniques in use require the unit to be probed. These require recoating at best, and risk card damage at the worst. An alternative to probing is to generate a fault matrix to allow fault isolation based on a set of fault signatures, however it is frequently not possible to store all possible fault matrices. AI may aid in the development of simulating the faults while the test is in progress. Present work on expert systems at MIT and Stanford is in the area of causal knowledge in which AI aids in modeling the operation and function of a unit. Recent work by Davis at MIT, applies causal modeling to diagnostics (27). In his approach,

most of the knowledge that would be needed by a technician to diagnose a problem is included as part of the expert system. Work in this area is also being done by Genesereth (26) in his DART project.

The usefulness of causal knowledge is in dispute by some of the AI community, but the general consensus is that it will play a large part in future expert systems. There is some risk however, because no concrete evidence has been shown that the use of causal knowledge will be practical within the next three to five year time frame.

4.3 DISCRIMINATION BETWEEN FALSE ALARMS AND INTERMITTENT FAULTS

Discrimination between false alarms and real faults is one of the toughest and most controversial aspects of testing. The definition of false alarm is "an indicated fault where no fault exists" (see glossary, 9.0). The Integrated Test and Maintenance study done for AFWAL (1) concluded that in order "to eliminate the false alarms due to design defects, the only solution is a design and test effort." Modifications to both the operational hardware and its BIT during full scale development as part of the design process of a program can eliminate a majority of these false alarms. During full scale development it would be more appropriate to refer to those alarms as design deficiency alarms, and only after that phase refer to them as false alarms. False alarms caused by environmental conditions such as voltage transients, electromagnetic interference, dust, background radiation, side-effects of other system failures, or operator error are defects which can often be eliminated during initial testing.

All approaches have no magical techniques for discriminating between false alarms and intermittents. All cannot go beyond the information provided by people and field data. The Integrated Test and Maintenance project (1) proposed a fault classification expert system that would discriminate between false alarms and intermittents. All provides a means of acquiring the field diagnostic experience and organizing it for cost effective use. With this field experience information, a determination can be made if similar units will give a false alarm when presented with an identical environment. Intermittents, on the other hand, generally occur only for a particular unit and frequently evolve into hard faults. In a discussion on Maintenance Expert Evaluation in section 5.5 (figure 5.5-2) we

predict the capability to descriminate will not come until maintenance experts become smart in their ability to use the field information and improvements in DFT and Smart BIT are made. This will take at least five years.

4.4 REDUCING SKILLS REQUIRED FOR MAINTENANCE

The Air Force has identified a need to reduce the level of skills required of maintenance personnel. One problem is because more systems are being developed directly using computers, they are difficult to understand without also using a computer. Another problem is that in recent years only relatively less skilled military personnel have been typically available due to the difficulty in recruiting, training, and retaining qualified people. Maintenance expert consulting systems and computer-aided instruction systems are two solutions normally considered for reducing required skill levels. But because of increased system complexity the ability to reduce skill levels is largely a myth; even the best test capability will not solve 100% of the test and maintenance problems. Skilled technicians will still be needed for the tough problems, even if they occur less frequently.

4.4.1 Maintenance Expert Systems Reduce Required Experience

Current military ATE systems require that technicians acquire a great deal of specific experience for each item they are to diagnose. This is acceptable for high volume commercial testing where a technician maintains only a few items, and thus can gain the diagnostic experience in a few months. However, a military technician who must maintain hundreds of different items using ATE will require several years to gain much experience on most items, at which point his term of duty may be over.

By providing the technician with easy access to past information presented to him in a relevant fashion for the specific box being tested, he can become efficient on his job much more quickly. The types of information that the AI applications described in this report can provide are:

- o Information concerning the field fault history of the unit
- o Information on past similar faults and their diagnosis
- o An up-to-date schematic with related fault symptom information indicated

o Feedback of correctness of his diagnosis

If a specific fault with successful diagnosis has occurred before, the maintenance expert system would suggest that the same sequence of functional and diagnosis tests be performed again. It's worth pointing out, however, that although a number of expert systems and training systems have been built to aid in diagnostics of electrical and mechanical devices, none surveyed were designed to reduce the skills required for maintenance in the military.

Boeing Aerospace Company research on the application of expert systems to maintenance has led to a number of conclusions regarding maintenance personnel. First, in order to attain mission readiness, a maintenance technician requires a number of skills such as interpretation of maintenance manuals, choosing the correct tool for the task and being able to diagnose equipment faults effectively. Accomplishing these tasks takes not only ability, but time. Second, most expert systems presently in use assist the user only in a single domain, such as diagnostics. In addition, they do not give sufficient help at the skill level of the military user. Boeing research found that what is needed is a multidomain expert system that offers diagnostic capabilities, maintenance procedures, data collection, data analysis and help. At this time, Boeing Aerospace Company is conducting applied research on this type of a system; a prototype of the Maintenance and Diagnostic Information System (MDIS) is being built (37), and the concept has been shown to be feasible (see Section 2.10).

4.4.2 Computer-Aided Instruction (CAI)

Publications on computer-aided learning have shown CAI is not able to produce any significant cost savings in training compared to current techniques. Even with the use of video-discs there is not a significant increase in the amount of information retained or a decrease in the training time over conventional classroom techniques (40).

In a related approach, research has shown that it is feasible to have a maintenance expert system adapt to each user and determine his or her specific learning problems by analyzing responses. The system would then alter its training strategy to fit the particular user. Unfortunately, it does not appear that this type of system will be ready in the near term though the ability to adapt learning to each use is being aggressively researched by many organizations (41). Practical development is at least five years away.

4.4.3 Conclusion

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In the near term, AI cannot significantly improve pre-job training or perform diagnostic isolation; however, AI can now automatically acquire diagnostic experience from expert technicians and provide an integrated information display to all technicians. While not reducing the skill required, AI can reduce the amount of unit specific experience required. This should make inexperienced technicians more productive, their job less frustrating and more enjoyable, which may increase how long they stay on the assignments.

4.5 INTEGRATED DIAGNOSTICS

All military services are very concerned about the concurrent trends of increasing electronics complexity and the decreasing skill level of technicians. ATE has tended to remove the technician's intellectual capability from the testing process, so that his job is now very routine, and does not require him to "zero-in" on the problem. However, ATE still requires highly trained specialists to isolate the problems ATE can't diagnose, usually false alarms and intermittents.

After several years of study and meetings a program office has been set up for integrated diagnostics. The Integrated Diagnostics Program Office (ASD/AEGA at Wright-Patterson AFB) is very concerned that technicians be given some maintenance aids for all types of electronics faults. Now automatic testing in the system and ATE usually have hard fault diagnosis coverage in excess of 90%, but the most difficult diagnostic problems are still left to the maintenance technican. The problems of false alarms and intermittent faults give the technician an additional diagnostic burden. Non-AI techniques to improve automatic tests by incorporation of diagnostic experience are so manpower intensive that they are not cost effective, and are therefore rarely used.

All techniques will aid integrated diagnostics by providing tools to process information for use in design, operations, and maintenance. Artificial Intelligence presently does not have the capacity to 'think' in the classical sense, but can process information in the following ways:

o Logical acquisition of data

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- o Data analysis (pattern recognition)
- o Intelligent retrieval and display (including graphics) from database

If the information is not available in a given situation, AI cannot create it. AI will not be able to model the details of circuit operation until the late 80's (interview with Davis, Genesereth), but it can now record human diagnostic experiences and provide some generality to them so that when "similar" situations occur, the technician will be informed of the previous diagnostic experience. This is of some help for the expert technician who has a lot of diagnostic experience to draw upon, but its primary utility is for the average technician who does not have decades of general experience and years of system specific experience. In all near term applications, AI aids the technician in the performance of his task, but does not replace him. A maintenance expert system would be expected to improve the performance of all but the best experts (see figure 4.1-1).

The maintenance expert system provides diagnostic experience to the technician in the form of suggestions in context of the test in progress. The maintenance expert should graphically display the history of the current unit under test, and from its diagnostic experience database show a similar situation and what was done by the person at that time.

AI provides a cost effective means to incorporate the diagnostic experience for system testing, ATE, and bench testing. Integrated Diagnostics thus far has considered only two categories of tests: automatic and manual. The Smart Bench maintenance expert, which performs functional and diagnostic testing with bench test equipment, adds a new category between those two. It is targeted for those units normally tested on the bench or that are marginally acceptable for ATE testing. It provides a method to capture detailed functional and diagnostic information from bench testing. (See Section 5.8)

4.6 DESIGN FOR TESTABILITY

Testability, as it now stands in the industry, is a "bottom up" process. Virtually all the known techniques require a detailed circuit design before a system's testability can be calculated. However, design is a "top down" process. The designer is given requirements for design, creates a design approach, analyzes it for performance, selects an architecture, defines subsystem structures and performance requirements, and, finally, evolves a structural design that can be analyzed for testability. It is very difficult for an electronic designer to consider all of the testability requirements of a given product. The knowledge needed requires a testability expert to be available during the design process to consult with the designer. Table 4.6-1 shows some of the testability knowledge that this study found is needed during design. A methodology is needed to handle DFT techniques from the top down. One approach is described in "Computer Aided Testability," (2) where the potential use of AI techniques was mentioned:

"A number of terms have been developed to describe the various levels of a design in going from subsystem to detailed level. The top level is referred to as the "behavioral" level. Typically, at this point, the design has not been committed to hardware and the prime emphasis is performance. The next level has been described as "functional" or more recently "architectural." At this level, a particular implementation has been defined— analog, digital, mechanical, etc. Within the architectural level there are further subdivisions. "Microarchitecture" has been coined to define the top level structural details, typically in a register level form. A lower level description in this same level is the "logical" description in the form of schematics that have not been committed to specific parts. The west level, excluding semiconductor design, is the "structural" level (or "physical") which defines in detail the specific manufacturing process, e.g., interconnects, parts, etc. Typically it is at this level that most testability analyses are currently performed today. In effect, these analyses are after the fact audits, and DFT is often ignored." (See figure 4.6-1)

Knowledge Needed Requires Testability Expert

- Military system requirements
 - Short test times requirements
 - Fault tolerance requirements
 - Availability
 - Production
 - Operation
- Factory production/test generation
 - ATE: Functional, in-circuit bench
- Maintenance/reliability
 - System availability
 - Maintenance cycle, experience level of technicians
 - Integrated diagnostics
 - Diagnostic concept BIT/ATE trade
 - Bit selection (dozens of types)
 - Must diagnose all faults at all levels of maintenance
 - Data collection and test improvement
 - Effect of intermittents false alarm rate
- Corporate design rules (LSSD, etc)
- Costs of testability
 - Weight volume
 - Memory constraint
 - Production costs
 - Reliability degradation due to additional circuitry

Table 4.6-1 Testability Requirements

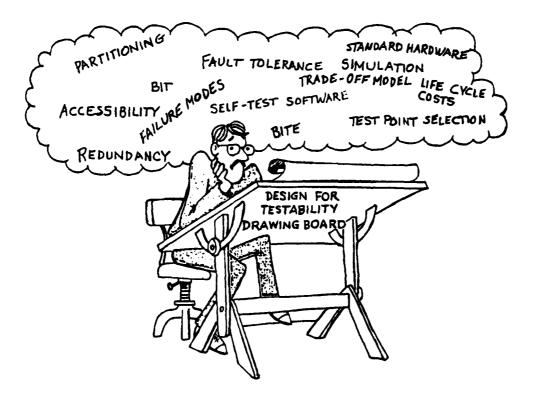


Figure 4.6-1 Design for Testability Drawing Board (49)

A potential AI solution to this DFT problem is covered by the computer aided preliminary design for testability opportunity described in section 5.3. The RADC testability notebook shows (figures 4.6-2 and 4.6 3) that testability incorporation during preliminary design has the largest impact (70%) on life cycle costs so this study is evaluating the use of preliminary rather than the typical post DFT aides



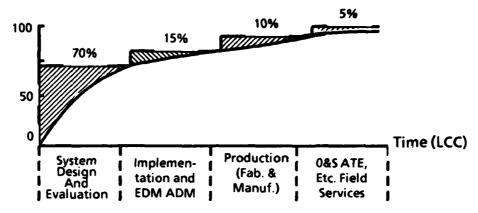
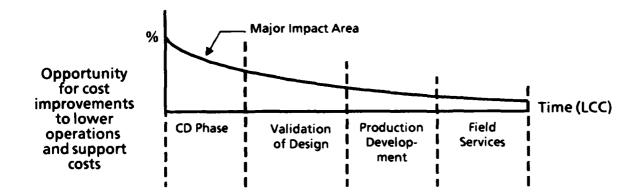


Figure 4.6-2 Testability Incorporation During Preliminary Design, Has Largest Impact (22)



"Intensive total system design analyses are essential for lowest operations and support cost, by proper design for PM, FD/FL (BIT/BITE) integral with system (70% impact potential)".

Figure 4.6-3 Opportunity for Cost Improvement (22)

5.0 POTENTIAL AI SOLUTIONS TO TESTABILITY PROBLEMS

5.1 INTRODUCTION

The survey of AI techniques, ATE/BIT, and testability applications permitted consideration of many possible AI applications to testability. The many factors affecting the desirability of an AI solution are discussed in section 5.2. The applications are coalesced into specific solutions (opportunities) which are discussed in sections 5.3 to 5.9, often with the aid of figures predicting their evolutionary development. The requirements for the development and use of the AI applications are met by the engineering work station (see 5.10). The detailed evaluation of the solutions follow in section 6.0.

Some key findings of this section are:

- o Computer aided preliminary design for testability can create the testability expert needed for early phase DFT reviews
- o Smart BIT—first needs to record field fault data, which can be done with a programmable-recording BIT chip set, and then evolve into incorporation of AI techniques
- o Maintenance expert systems
 - o cost effective now; will increase their ineffectiveness as tools (rules) are developed to ease their creation
 - o evolutionary development will greatly increase their capability
 - testability improvements are necessary to make full use of the increased capability
 - o maintenance experts for ATE, bench, system used on-line and off-line share many development features, but have different benefits and risks.
- Engineering work stations meet the requirements for development and use of the solutions

5.2 INITIAL EVALUATION OF AI APPLICATIONS TO TESTABILITY

Since the goal of this study was to find practical and cost effective applications of AI to testability, those applications identified during the survey phase, with little potential, were eliminated. The development of testability needs and a listing of applications rejected is covered in this section. The cause of rejection generally was due to the necessity of waiting for a heavily funded AI research effort to develop a cost effective tool or because the application would have a very small market.

5.2.1 Military Testability Needs Are Emphasized

Military and commercial testability needs differ in many ways. Some AI applications, while being useful for commercial applications would not be cost effective or desirable for military products. Military testability has certain requirements:

- o Low volume production
- o High stress environment that results in increased intermittents
- o High complexity yet restricted test access due to conformal coating
- o Distributed repair by low skill/short longevity personnel
- o Old ATE with slow and limited ability test programs
- o Fault tolerance and BIT used more than by commercial products.

Commercial testability needs are different and include:

- o High volume production.
- Need for rapid testing on production line
- o Use of VLSI in designs
- o Use of state-of-the-art components and ATE
- o VLSI Design must be correct the first time due to competitive market
- o Production line testability emphasis rather than field
- o Test and repair by board swap is extensively used

 (Field service is not as concerned with component isolation)
- o More benign operating environment (except for automotive electronics)

These differences need to be considered when judging the practicality of applying AI to military testability needs.

5.2.2 What Makes an Application Desirable

Applications which create very unique or identifiable benefits were the prime consideration of this study, that is, the application would:

- o Perform jobs not previously done due to lack of effective tools
- o Result in general purpose tools which can be widely applied
- o Provide significant downstream benefits
- o Use AI techniques already in use (and is therefore credible)
- O Create or use breakthroughs which had the potential of a 10X improvement over previous methods (examples are tools running on engineering work stations, machine learning, and metarules)

5.2.3 Desirability Factors

An application will be readily applied if it benefits all affected organizations. Each of the applications finally recommended (sec. 7.0) provide benefits (or at least no cost increase) to each of the following four types of organizations:

- o Military Projects
- o Support Organizations
- o R&D Organizations
- o Contractors and Subcontractors

Figure 5.2-1, Desirability of AI/T Applications, shows the relationship of the various factors that affect whether the military would want to use the application. The following paragraphs discuss key points of that diagram.

Does Military Project Want It?

The military project which controls an item's production contract does not want to take a risk with AI technology unless there is significant change in one of the following three items:

- o Does it improve mission critical performance?
- o Are acquisition costs reduced significantly?
- o Will it increase management visibility of testability?

Does Support Organization Want It?

The field support organizations have been "trained" by experience not to trust BIT indications, due to excessive false alarm rates. The accuracy of maintenance experts must support the requirements. For example, a flightline maintenance expert should have an accuracy of at least 90% if it is to be trusted and therefore used.

Large organizations do not readily accept change in their organizational structure. The AI information flow should be self-contained so that no organizational changes are needed.

R&D: Practicality of Demonstration

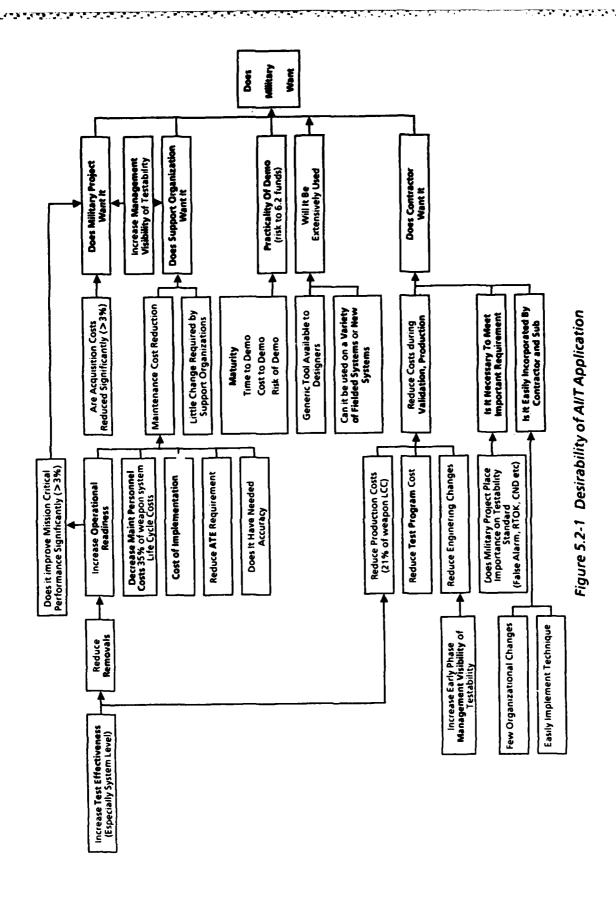
A major concern of a government research organization like Rome Air Development Center is the risk of successful demonstration of the concept. One of a research group's major product goals must be the successful demonstration of concepts. Because of this need, the following concept maturity aspects were explicity considered in our applications evaluation:

- o Time to demonstrate
- o Cost to demonstrate
- o Risk to demonstrate

Do Contractor and Subcontractors Want It?

A new testability technique should reduce the cost or the time to implement testability during the concept, validation, prototype, and production phases. Design for Testability employed at the concept phase should reduce the problems with all engineering development phases.

Prior to the field use it is difficult to assess the adequacy of the DFT process. When the testability requirements cannot adequately be measured in the early phases of the program (i.e., BIT verification is not easily performed for hard faults, much less intermittent or real world environmental faults), extremely expensive engineering change proposal (ECP) activity can result.



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The contractor will hesitate to use a technique if it requires him to acquire (or worse, develop) new design support systems or make major modifications to a design.

5.2.4 Potential AI Solutions to Testability Problems

A matrix of the key testability problems and the "mature" AI techniques is shown in table 5.2-1. This summarizes the interrelationship of these areas which were separately discussed in sections 2.0, 3.0, and 4.0. It comes as no surprise that expert systems are very useful for many of the problems. Machine Learning is an emerging AI technique which can semiautomatically create rules based on experience in a small fraction of the time required by rule based systems. Although natural language and voice recognition would be very useful AI techniques to be used with expert systems etc., they are not yet ready to be applied; at this point in time, improved graphics and on-screen manipulation techniques can provide a greater benefit than voice recognition. Discussion of some of the analysis details that went into the construction of Table 5.2-1 follows.

There were many suggestions available for solutions to improve testability using AI or pseudo-AI techniques. Input was taken from:

o literature search

- o industry interviews
- o corporate communications
- o statement of work for this study
- o integrated diagnostics meetings
- o Al conference
- o ATE conference

In addition to the desirability factors (fig. 5.2-1), this study was concerned with the practicality of development of a solution during the next three years and its payoff leverage. By far, the largest category of potential solutions used maintenance expert systems. Although present versions are cost effective, the use of breakthroughs in metarules, machine learning, and engineering work stations can provide a dramatic increase in capability and cost effectiveness of maintenance experts. The wide variety of these systems made it difficult to lump their benefits/risks into a single solution for description/evaluation. Therefore, several classes were created to clearly distinguish them. This topic is discussed in detail in section 5.5.

TESTABILITY PROBLEMS		MITTER	ONTHELLIGENT ONTHE BASENT	EXPERT SPEC	Moonics Jim	PATTER. PROGRAMMING	COMB PERCEPTION	MOTICE RECOGNITION MICHINE LEARNING
BIT/ATE FAILURE COVERAGE			¥	¥		¥	¥	***
SELF IMPROVING DIAGNOSTICS		¥	¥	¥		ML	ML	XXX
MORE EFFECTIVE FAULT DET&ISOL		¥		¥				XX
DISCRIMINATING INTER/FALSE				XXX		ML		***
REDUCING FALSE ALARMS	•	·		XX		·		XX
ISOLATING INTERMIT FAILURES				**				¥
REDUCING SKILL LEVEL FOR M	•	×		***		ML	¥	XX
TESTABILITY FOM				XX			¥	
DESIGN/TEST PROCESS INTEG.				***	¥	¥		
CAT COMPLEXITY AND COST			***	X	X			***
DATA COMPRESSION AND MANAGE.	•		***					XXX
INTERFACING AND UPWARD COMPAT.						¥		
MAN/MACHINE INTERFACE		XX				¥		

NOTES

ML MACHINE LEARNING IS USED N/A NO APPLICATION IN NEAR TERM

APPLICATION/IMPROVEMENT

X SOME
XX USEFUL
XXX VERY USEFUL

Table 5.2-1 AI Techniques Address Testability Problems

Of the following potential AI solutions to testability problems, those items preceded by an asterisk were selected for further analysis and are described in more detail later in this section.

- * Computer Aided Preliminary Design for Testability (CAPDT) provides a testability assistant directly available during preliminary design phases.
- * Smart Built-In Test used in boxes or cards can identify intermittent faults and reduce false alarms.
- * Smart System Integrated Test is a system level Smart BIT which performs testing while the system is operating.
- * Maintenance Expert Box provides ATE test management with self improvement of functional tests.
- * Maintenance Expert System describes the kind of capability that can be expected during the next three years.
- * Maintenance Expert—Smart incorporates the benefits/risks of the evolutionary insertion of learning capability in the maintenance expert—system and its access to Smart BIT information.
- * Smart Bench is a maintenance expert system to semi automate bench testing.
- * Automatic Test Program Generation (ATPG) can create better functional tests if AI provides ability to understand circuit functional operation level.

Maintenance Experts with Circuit Understanding techniques is not ready; by itself AI will take at least 5 years to understand today's circuits. This also relegates AI to an information manager.

Robot-ATE test. Military tests are so slow that handling time is insignificant. It is pointless to reduce a one minute handling time for a one hour test. GenRad and Zentel have developed this for commercial applications with production volumes of over 1000 per day. This AI application is most applicable to high rate production environments.

Computer Aided Instruction results in neglible cost saving at this time.

Natural Language Interface techniques are rapidly developing and heavily funded by many organizations. However, tools are not yet available for use with other AI techniques and use of graphics is a less risky way to communicate electronics information in the near term.

ATE Replacement Aids facilitate the transfer of tests from old ATE to new. Costs to develop each aid cannot be amortized, so manual techniques remain more cost effective.

Software Assistant for Test Program Development is not cost effective in the near term. Heavy funding currently is being applied to the general software assistant; examining testability utilization of it should wait a few years until the software assistant is a well defined product. Additionally, the lack of ATE standard hardware and software and a means to fully describe the unit under test will make it difficult to make a general purpose test program set (TPS) assistant.

The following sections present concept details of the AI applications selected for analysis.

5.3 COMPUTER AIDED PRELIMINARY DESIGN FOR TESTABILITY (CAPDT)

Computer aided preliminary design for testability (CAPDT) is a testability expert which can access testability during early phases of design.

The findings related to this application are:

- o Testability experts are needed during initial design to meet new requirements.
- o Not enough human testability experts are available.
- o An AI testability expert can be made.
- o Research is currently underway that supports the concept.
- o Large benefits in total LCC as well as decreased production phase cost are possible.

Development Status

To date, all development in this area has been concerned with the manufacture of very large scale integration of circuits (VLSI), where the lack of testability and self-test can result in an integrated circuit slipping its schedule and thus loosing its position in that aggressive market place. "A Merger of CAD and CAT is breaking the VLSI test bottleneck" (35) and "Automation in Design for Testability" (38) are recent overviews of VLSI DFT.

5.3.1 Need To Apply Testability Expertise During Initial Design

Manual and computer aided testability audits are characteristically applied too late for results to be incorporated into the design and typically have too narrow a focus (e.g., focus on only ATE). As a result, low testability has caused high operations and maintenance costs due to false alarms, intermittent faults and diagnostic isolation ambiguity. A testability expert working with the designers during preliminary design can provide suggestions and comments that will improve insertion of testability. To do this effectively, the expert needs knowledge of the design hierarchy from the integrated circuit up through system level design.

The IDA Test Technology Report pointed out the LCC reduction benefits from early testability insertion:

- "Designing in testability on new weapon systems had the highest potential of all approaches in testing technology research and development. A 10% to 20% reduction in the life cycle costs can be achieved by employing good testability design."
- They also recommended that the military "initiate a major weapon system design technology program, which injects testing technology into this design process."

5.3.2 Few Testability Experts

Electronic system designers cannot be expected to be aware of all of the test considerations which need to be traded; it is difficult enough just to understand the dozens of testability requirements levied against a program (see section 4.6). More testability experts could be trained, however; there are no standard means to evaluate their work and it is very difficult for one individual to have awareness of all system levels test requirements and trades. All provides a way of cloning the human testability experts, and making them available to designers. The resulting man/machine system will not be overloaded with information the way the human would.

5.3.3 Description of CAPDT

Computer aided preliminary design for testability is a rule based testability assistant which can be developed for engineering work stations to provide testability reviews/assistance, computer aided learning, and provide suggestions at the early phase of the system development (fig. 5.3-1). This testability assistant would be used to improve testability and thus produce cost reductions at all subsequent phases of system development. It would also support electronics design at all levels of implementation from system design down to integrated circuit design.

In order for CAPDT to analyze a circuit it must first be recognized. "A High Level Recognizer for Schematic Diagram" (IEEE Transactions on Computer Graphics and Applications May 1983) shows the progress in automatic circuit and network recognition. CAPDT would, in the near term, have man-aided computer recognition, where the machine would ask questions about functionality and testability of the network. The

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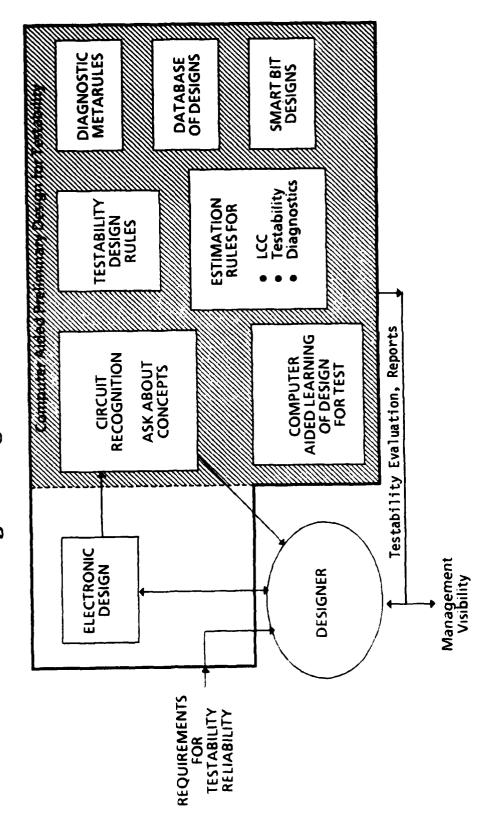
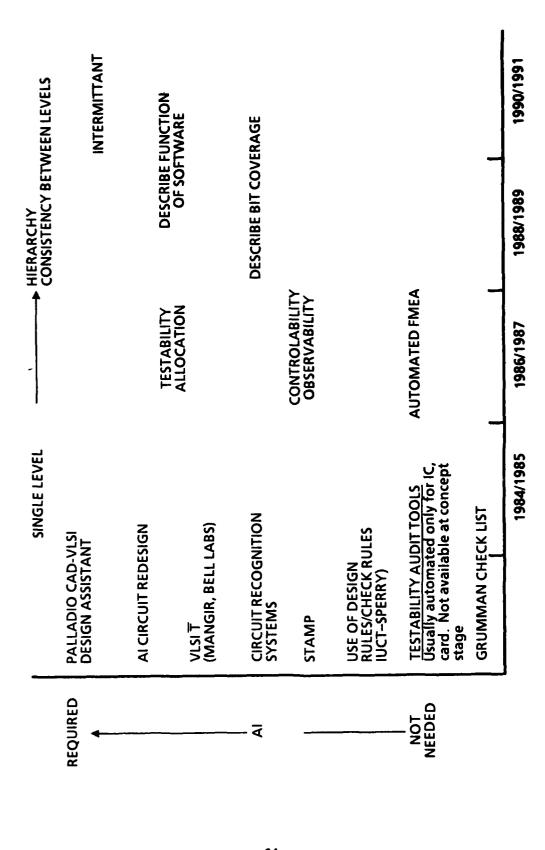


Figure 5.3-1. Computer Aided Preliminary Design for Testability



Computer Aided Preliminary Design for Testability Evolution Figure 5.3-2

following hypothetical design or interaction with DFT system is taken from Horstmann. "Design for Testability using Logic Programming," (32):

Designer Input	System Response										
Start DFT Check CLK1 cannot be observed. What should I do?											
Why can't you observe CLK1?	Failed to connect this clock to an output.										
Connect it.	I have added an additional output (PO2) for CLKI.										
Continue with check.	CLK2 cannot be observed. What should I do?										
Continue with check.	I have added an additional output (PO3) for CLK2.										
	The design is correct as it currently stands.										

This interview session with the "testability expert" would produce a tabularized description of the network attributes similar to FMEA and Dr. Pau's work (see sec 2.4).

CAPDT would have several classes of resources to draw upon using intelligent retrieval techniques:

- o Design rules for BIT, Fault Tolerance
- o Testability estimators
- o LCC estimators

- o Information Base of previously analyzed examples
- o Diagnostic metarules

Testability information can also be provided to the designer in the form of examples of test strategies previously used for similar requirements/constraints. Installing a testability tutor of this type on an engineering workstation can provide a very powerful teaching tool. By having a very large database which can be altered, it can predict the effect in change of test strategy. It can have examples of good and bad BIT, self test, reliability designs etc.

5.3.4 Status and Evolution

A form of CAPDT is being developed for integrated circuits in the commercial market place and for VLSI and the military market place through the VHSIC development. Mangir (34) discusses the use of expert systems for assessing the design tradeoffs during preliminary design of built-in self-test for VLSI.

Steinberg (AAAI-1983) "An Intelligent Aid for Circuit Redesign" extends his work at Rutgers on CRITTER to evaluate options for changing a digital electronics design. Redesign has much less scope than design, so is much more tractable. The ability of AI to suggest, then investigate the impact of redesign is just what is needed for CAPDT.

Section 8.2 has additional pertinent references. The CAD section shows IBM extensive work in this area: "Structured Design Verification: Function and Timing". A review is given in "Prospects for Expert Systems in CAD" (Stefik 83). The testability section has "Design for Test Calculus: An Algorithm for DFT Rules Checking" which is a one-pass algorithm for checking digital networks, especially VLSI IC's.

There will be an evolution of the capability of CAPDT with the initial systems having the ability to impose design rule checks, perform testability allocation, investigate controllability and observability and aid in suggesting and performing trades such as self-test versus external test capability. These systems will be able to evolve in several years to include the ability to describe software functioning, especially for self-test coverage and perform a hierarchy of testability allocation between the system, subsystem, box, card, and integrated circuit levels (fig. 5.3-2). It will be at least five years until this system has the capability of considering effects of intermittents in the testability coverage.

5.3.5 Concerns/Risks

There are several aspects which can limit the near term use or capability of CAPDT:

o Restricted usage due to design station diversity (lack of standardization)
Other design stations used (VAX etc.)
Other modeling systems used during preliminary design,
i.e., computer hardware description language

- o Near term limitations

 Designer must describe function performed by software
- o Intermittents difficult to deal with

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o National accumulation of a database will be restricted by corporate interests

As recommended later, in section 6, there should be an active program to standardize the data interchange format for all of the AI solutions to testability so that the knowledge can be shared.

The restrictions on describing software and intermittents will require use of some approximation techniques to provide descriptions in the near term.

Knowledge defines the capability of CAPDT, and more knowledge is obtained by having more users input information into the same knowledge base.

5.4 SMART BUILT-IN-TEST (BIT)

As described in the RADC work statement for its Smart BIT procurement, "Smart BIT is a design concept capable of identifying intermittent faults, reducing false alarms, and discriminating between the two. It is being implemented in part by the general use of artificial intelligence techniques." It does not use AI to the exlusion of normal BIT techniques. Smart BIT can be used with boxes or cards of electronics. Self test at system level and chip level, while also needing improvement, has different requirements which are outlined at the end of this section.

The Smart BIT discussion will proceed as follows:

- o A programmable recording BIT chip set is needed as a minimum.
- o Smart BIT improves diagnostic techniques of programmable-recording BIT.
- o Signal analysis similar to a technician's approach can be used.
- o Review of status and risks.

5.4.1 Programmable-Recording BIT Chip Set is Needed as a Minimum

The requirements for improved BIT capability discussed in section 3.1 can be at least partially satisfied with a microprocessor based BIT which is reprogrammable and can include environmental information along with a fault record. Maintenance technicians and maintenance expert systems have a vital need for this kind of data to reduce RTOK incidence. By providing good fault recording capability the programmable-recording BIT can also capture fault information during design and full scale development which can lead to the elimination of false alarm causes. False alarms can be reduced after full scale development by software modification to the programmable BIT. Even though changes to software or hardware after configuration control has been established are usually very expensive, it is possible that the design approach and previous verification/validation of the BIT will have proven independence of test routines, thus allowing a simplier V&V effort.

At this time, BIT is usually invented for each project and is rarely programmable. This has, in the past, resulted in most testing organizations not trusting BIT. Improved capability of programmable-recording BIT or Smart BIT must be provided with good interfaces to the designer, the user and the maintenance technician if it is to be accepted and trusted.

5.4.2 Chip Set and Software Will Reduce Development Time and Cost

Present technology has the capability to develop a programmable-recording BIT chip set for the military that would occupy only a few square inches of board area. (Within two years time, this can be reduced further by use of leadless chip carrier technology.) The read only memory chip can contain proven software test routines that can be used by any designer, eliminating the need for each person to reinvent, debug, verify and validate totally new BIT appraches for each design.

The read only memory will need to contain a real time operating system and a method to connect the independently developed routines together. The concept "pipes" of the UNIX operating system, which allows the output of one process to directly flow into the next can be used here. UNIX permits independent pipes to be created and tested which can later be joined together into a needed configuration. The need for assembly language programming by each BIT designer should be virtually eliminated by the previously developed and validated pipes.

A major requirement of this new BIT capability is that it be able to perform its own self test. This would include routines to test its processor and all types of memory, and loop around a majority of its input/output circuitry. It should also be designed to fail in such a way so that the failure of BIT is clearly distinguishable from the failure of the functional unit, in addition, a BIT failure must not cause the failure of the functional unit.

5.4.3 Bit Chip Set Description

CONTROL OF THE PROPERTY OF THE

Figure 5.4-1 shows that there is a variety of memory utilization in the chip set using different types of memory chips. The resources are in read only memory, and implementation of the test requirements are in non-volatile (information stored is not lost when power is removed) memory. Environmental information would come from the system level and be recorded with faults in the non-volatile memory. (Strike (48) has a good review of electrically erasable- programmable read only memory (EEPROM) for avionics that fits this application.) The ATE/Engineering work station connection to the chip set would provide for reading of the fault data and reprogramming.

5.4.4 Smart BIT Improves Diagnostic Techniques of Programmable-Recording BIT

All can improve diagnostic capability of a programmable-recording BIT, providing the potential for systems to achieve an even lower level of false alarms and be able to perform some fault isolation of intermittents. Some of the AI capability can be internal to the chip set, but, in the near term, a majority of it will be in the engineering workstation because knowledge processing requires more memory than is currently reasonable to put onto a board.

5.4.5 Detailed Descriptions: Browsing BIT

One promising SMART BIT concept is that of a roving signal analysis which we have termed "Browsing BIT". It has the potential to reduce the amount of dedicated resources, but, upon demand, can focus its attention on circuits having intermittents. The "Browsing BIT" surveys signal quality in a semiautonomous manner. It would be able to detect a substantial, abrupt or irregular change in the condition of the signals monitored to aid in discrimination between false alarms and intermittents.

The browsing BIT would have many of the capabilities of a nonexpert electronic technician instructed to monitor all of the inputs and outputs to see if they meet their specifications. They both could, for example, report when the signals are degraded. The Browsing Bit would perform these tasks in places where the technician could not be present, e.g., inside a missile in flight.

ATE tends to ignore signal quality and intermittents which are the focus of Browsing BIT. Pulse signals, for example, could be monitored for amplitude, noise, and multiple or sharp pulse in addition to the standard duration measurement.

Browsing BIT would have many means at its disposal to test signals and their interrelationships. To better understand what is and is not a failure, it would have an ability to set its internal "Browsing" tolerances tighter than its alarm tolerances. By doing this it would acquire more information about the characteristics and operating conditions associated with each fault or signal degradation. This would permit the future prognostic capabilty shown at the far right of the BIT evolutionary chart fig. 5.4-2. A Browsing BIT would spend varying amounts of time on each of the following four functions depending on recent fault history:

- o Test that each parameter is within functional specification
- o Monitor quality of all signals
- o If signal deterioration is observed, increase monitoring all signals that could have affect on it
- Acquire good signal characteristics and record in nonvolatile memory for external analysis during program development and verification

While the "Browsing BIT" does not monitor all signals 100% of the time and can miss detecting some intermittents, the ability to force the unit to spend more time on critical circuits or likely fault areas as well as its ability to concentrate on these areas when faults occur, permit a significant increase in observability of likely fault conditions.

5.4.6 Chip Set Signal Analysis Tools Are Modeled After Technicians Tools

A combination of hardware and software signal processing modeled on a technician's signal processing testing capability can provide a powerful set of programmable analog circuit test capability.

Signal filtering can be provided in both the analog circuitry and software. This allows checking for both in-band and out-of-band signal components. Measurements can include frequency, DC volts, AC volts, peak/valley, while computations can include voltage ratio, phase, etc.

The BIT, as shown in figure 5.4-1, should have the ability to inject test signals. A remote 8-channel signal selector integrated circuit would reduce the number of interconnections by providing control with a single wire. Signal injection would be through a programmable series impedance or attenuator.

Digital BIT would be able to build upon the analog tools. It could add an integrated circuit to the chip set to provide signature analysis, transition counting, logic analysis, and circuits to look at risetime or jitter.

5.4.7 Benefits

Smart BIT and Smart System Integrated Test (see section 5.6) provide virtually the only means found by this survey to reduce false alarms as well as being able to provide enough

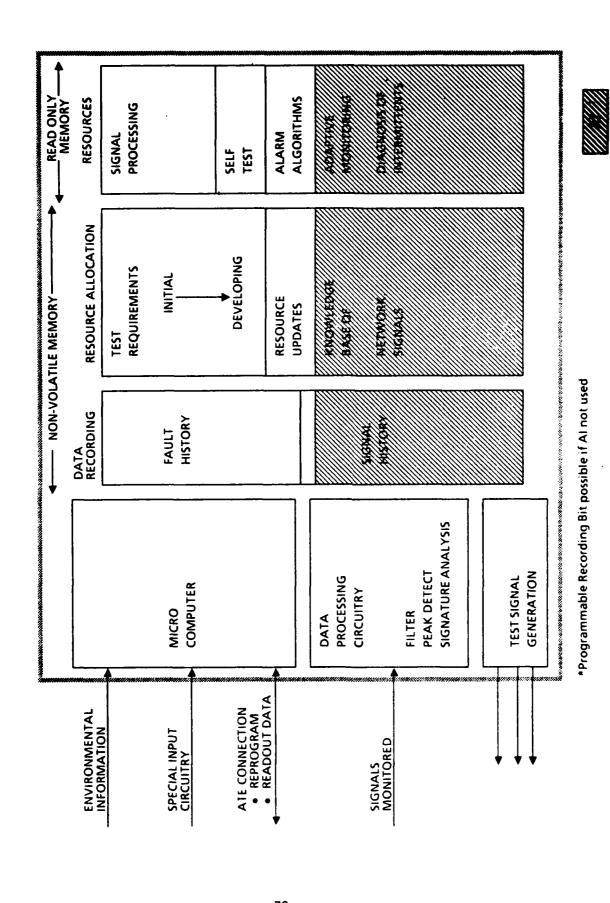


Figure 5.4-1 Smart BIT Chip Set

information to the maintenance expert to reduce unnecessary maintenance. In addition to the high payoff resulting from reduced maintanance costs, Smart BIT can also reduce contractor costs by providing a tool to detect and isolate faults during the full scale development phases, thus reducing engineering effort.

5.4.8 Developmental Status

The RADC Smart BIT contract award (February 84) to Grumman Aerospace is the only known work in process. The evolutionary potential of Smart BIT is given in figure 5.4-2, along with an estimated practical time scale for the development.

The Artificial Intelligence Application to Maintenance Technology (3) report stated that a complete series of studies leading to the design of an on-board knowledge based monitoring system or the design or test of experimental BIT systems would run 2 to 4 years and cost one to six million dollars. Benefits are incalculatable since they include the worth of reduced mission aborts due to false alarms. More tangible benefits could include a 90% reduction of false alarms, and the decrease of the portion of the units sent to repair which test "good" from the present 30% to perhaps 10%. The report speculated that successful application should pay for itself in two years of operation on one system and provide measurable improvement in the ready rate of the system using it.

5.4.9 Risk

The development of programmable-recording BIT/Smart BIT is technically straight-forward. Programmable-recording BIT could be developed on a practical basis now for some applications. Smart BIT requires more development, but this could be done after completion of the current RADC contract.

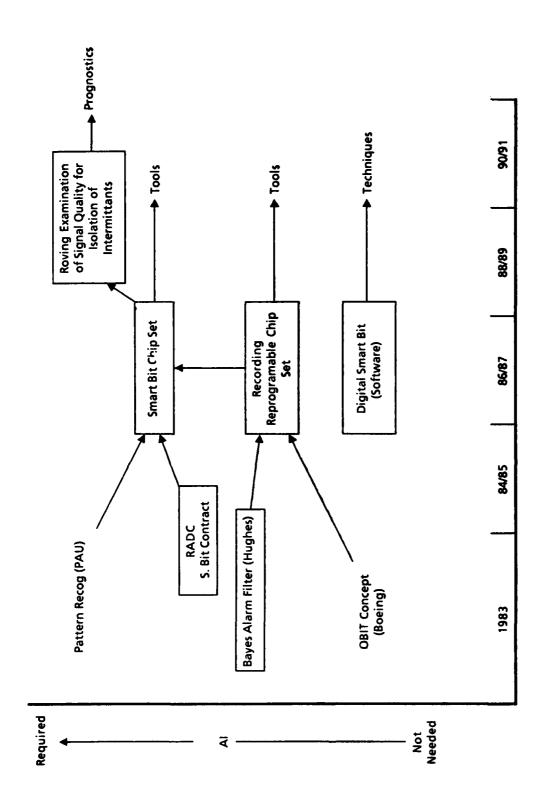


Figure 5.4-2 Smart BIT Evolution

5.5 MAINTENANCE EXPERT SYSTEMS

A maintenance expert system aids a technician in performing functional and diagnostic tests on boxes or systems online or offline. This is the most advanced application of artificial intelligence to testability and is well documented in the literature. There are several cost effective, generic, maintenance expert systems that process offline test information. The four at the top of the table 5.5-1 by GE, DEC, Battelle, and ICL have already been built and tested. In addition, the GE, DEC, and ICL systems saw factory use in 1983 while the much more powerful Battelle system was not released to end users. The fourteen other systems have not yet been as fully developed.

The findings of this section are:

- o Cost effective maintenance experts exist now
- o Five year evolution will include: self improving diagnostics, prognostics, circuit understanding, and discrimination of false alarms
- o An engineering work station is a practical device to add maintenance expert capability to ATE and bench testing
- o Testability improvements will further enhance the Maintenance Expert performance and cost effectiveness
- o A time critical Maintenance Expert requires high accuracy levels that are difficult to achieve without testability improvements
- Maintenance experts will improve diagnostic and functional test time for ATE

5.5.1 Maintenance Expert Systems Evaluated

There are five different categories of maintenance experts analyzed by this report which share many rules and methodologies and will follow similar evolutionary growth patterns. These range from bench testing through system level applications. The maintenance experts were split into these five sections so that evaluations and recommendations could be made separately for each application, because of the wide differences in the applications. The maintenance experts are:

- o Smart System Integrated Test
- o Maintenance Expert-Box
- o Maintenance Expert-System

			ď	Dev Level O → 5	5		Farliest	Al Theory	Adamt/	Circuit
Organization	Reference	Project	System	Subsyst or box	Card	Unit Diagnosed	Year Ready for Field	Develop- ment 0 → 5	Learn 0+5	Knowledge 0→5
95	(83) rewis	Delta, Gen-X	3	3		Diverse	1983	0	0	0
DEC	Shubin (82) (Int)	Intelligent diagnostic tool	4			PDP-11 computer	1983	1	0	0
Battelle	Pau (83) (84)			3	3	Diverse	1983	5	7	3
Inter Computer Ltd.	Hartley (84)	CRIB		4		computer	1982	2	3	-
Ē		PEAM	2	7		Diverse	86-87	1	0	0
Boeing	Partridge (83)	Integ test and maintenance	-			Aircraft	-	0	0	0
Stanford	Genereseth (82)	Dart II			2	Combinational circuits	88-90	5	•	s
MIT	Davis (83)	Hardware troubleshoot			2	Combinational circuits	88-90	5	•	S
Yale	McDermott	ARBY		2		Electronic sys.		3		-
Magnavox	Arington (83)	Experience algorithms		-			-	0	3	0
Navy Research Laboratory	Cantone (83)	IN-ATE		2		Tektronic 465		0	•	•
Rutgers	Sternberg (82)	Critter			7			2	-	2
Lockheed	Laffey (int)	LES	7					0	-	•
Xerox	deKleer				-			\$	'	•
DETRIX		LOGMOD							-	
ARINC	Simpson (83)	STAMP	5	5		Avionics systems			2	_
McDonnel Douglas	Miller (Int)				1	Power supply		0	0	-
Battelle	Kelley (83)	Machine self- diagnosis	-		-	Jet engine		-	-	0

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Operating on large circuits Used internally for diagnosis Used externally for diagnosis Thinking or old work Funded study or IR&D Operating on toy circuits

Table 5.5-1. Maintenance Expert System References

- Maintenance Expert-Smart
 (includes Smart BIT and learning capability)
- o Smart bench

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An overview of the features in these expert systems is given in table 5.5-2.

FEATURE	SMART SIT	M.E. BOX	M.E. SYSTEM	M.E. SMART SYSTEM	SMART BENCH
Unit tested	System	Box	System	System	Box, Card
On-line test	Yes	No	No	No	No
Location of testing	Field	Depot	Field- Intermediate	Field- Intermediate	Depot
Reduce removals from system	Yes	No	Yes	Yes	No
High accuracy needed due to time critical task	Often	No	Sometimes	Sometimes	No
Reduce false alarms	Yes	No	No	No	No
Smart - Optimizes tests and learns diagnostics with aid of smart BIT	Yes	No	No	Yes	Yes
Cost Effectively applied to units in field	No	Yes	No	No	Yes

Table 5.5-2. Maintenance Experts Overview

The performance of the expert systems is very dependent upon the unit's inherent testability and ability to record sufficient data fault. Maintenance experts will be able to evolve in three to five years time into SMART Maintenance Experts having the ability to learn by SID and getting information from SMART BIT. Initially the maintenance expert would only have knowledge of a fault tree and be able to modify functional test sequences, but later capability could be added to automatically acquire diagnostic information.

Maintenance Expert System, Approaches That Were Not Evaluated.

Research aimed at having AI understand circuit operation and faults has been going on at Stanford, MIT and Xerox. This work is summarized in table 5.5-1 as having high circuit detail knowledge, and all of their developers, when surveyed, agreed that at least 3 to 5 years would be needed before practical use is possible. Card level maintenance experts were not included in this study due to lack of maturity of circuit understanding by expert systems and since the commercial card testers with ATPG do an acceptable job.

Other special maintenance experts (such as Bell telephone's ACE which uses AI to find a common source of telephone cable fault reports) were not included because they did not appear to have as widespread use, or solved needs which currently don't apply to military testability.

Evolution of Maintenance Expert Systems

Maintenance experts, being a subclass of rule based expert systems, can often explain themselves when called upon, but they have a limited scope of knowledge. Within that scope of knowledge, the maintenance experts act very similar to the human in terms of being able to process information associated with functional and diagnostic testing. Maintenance experts differ from rule based expert systems only in scope of material. The maintenance expert's extremely limited scope of knowledge (electronic testing) is now allowing the creation of generic maintenance experts which can be reapplied to many systems.

Step One: Offline Maintenance Expert:

The first stage of evolution (figure 5.5-1) is as an off-line aid that can suggest which tests should be made based on previous tests. The Gen-X system has this capability. The DEC Intelligent Diagnostic tool (IDT) is on-line, but does not learn diagnostics or functional test optimization. Current versions of both might be described as automated dependency chart analyzers.

ARINC's (Aeronautical Radio Inc.) on-going development of STAMP (System Testability and Maintenance Program-(29)) has resulted in the optimization of test sequences based on failure history at a single ATE test site. The Apple computer which is the STAMP host

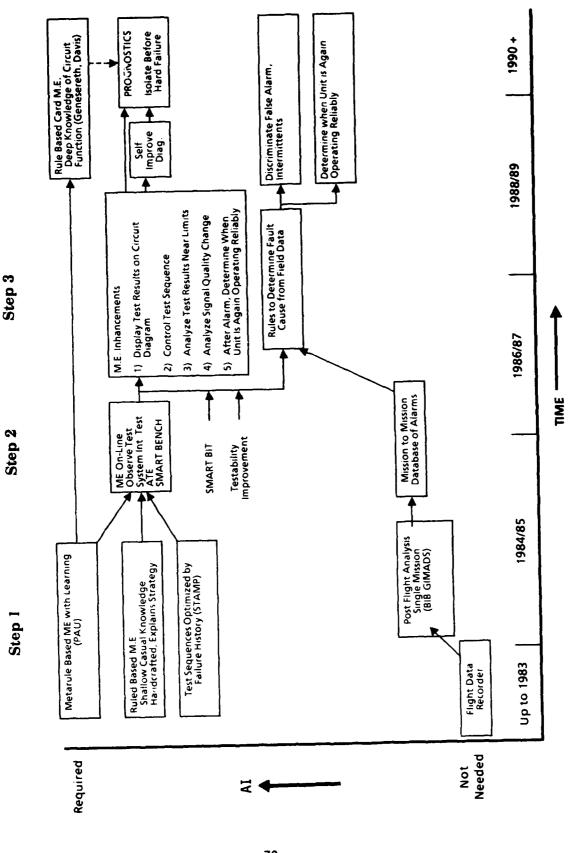


Figure 5.5-1 Maintenance Expert Evolution

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does not yet have any direct ATE connection. Future versions of STAMP with another host computer may evolve into on-line use.

From the present off-line capability, the systems will evolve to on-line observation, and then enhancements can be added which utilize the power of AI to control, interpret, and analyze the test in progress. The anticipated evolution from 1983 to 1990 shown on figure 5.5-1 will be discussed in the following paragraphs.

Step Two: On-line Maintenance Expert:

The next phase of evolution of the maintenance experts will be the combination of rule based maintenance experts and test sequence optimization. This will allow developers to produce a maintenance expert that can observe tests in progress at either the system, ATE, or bench test level, capture data and provide test enhancement form the data. (Note: Dr. Pau's work may have already progressed to this stage. His modular system has demonstrated combining of vision information and card test information).

CRIB, a Computer Retrieval Incidence Bank expert system (10), is used for computer hardware and software fault diagnosis. Knowledge is added to it by maintenance personnel giving it self improving diagnostics from an aggregate of users. Its daily use provides its validation. Knowledge from previous test results provides groups of symptoms which can uniquely identify a fault. It is not necessary to have a complete match of symptoms. CRIB is based on a small, fixed set of rules and meta-rules and a large, changing body of data. This MYCIN-like maintenance expert system (16) has been in use at International Computers Limited for several years, and as such, is the most mature system reported in the literature.

Modular Maintenance Expert

A maintenance expert can be used with many different environments, different ATE and with bench testing as shown in figure 5.5-2. The connection to the ATE for observation can be as simple as monitoring the line which connects the ATE with its system console, generally an RS-232 interface. Most of the commation concerning test step number and results of the tests is available on this line. In some cases it may be necessary to have an additional connection or to monitor the ATE line printer. This modular maintenance expert approach has the capability of doing all of the information processing mentioned in

the introduction to this section, including acquiring test information from the ATE, storing it, analyzing it locally, and distributing this information back to the central site for incorporation in diagnostics. Engineering work stations have the capability to provide a common connection, without modification, to many military ATE.

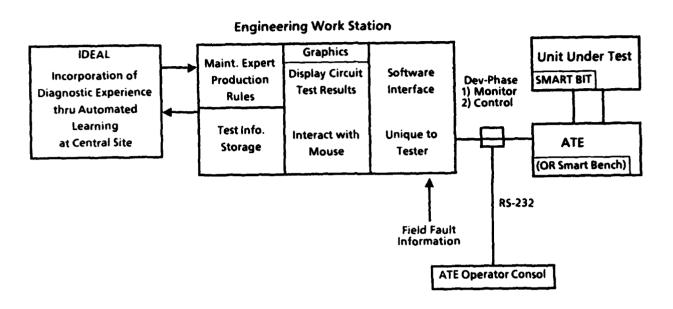


Figure 5.5-2. Modular Maintenance Experts.

Step Three Modular Maintenance Expert Enhancements

The next phase of the maintenance expert's evolution involves enhancements to the modular maintenance expert's capability. These five enhancements are essentially independent, and can be implemented in any combination or sequence.

1. Integrated Display

The modular maintenance expert will be able to provide an integrated information display on its graphics screen. This will provide the test technician with much additional, relevant information. Data concerning the current and past results of the unit under test can be superimposed upon the nodal connection diagram of the unit. Color would provide the best display. Even though color is not widely available on engineering work stations today, it should be readily available by the time this step is implemented. The graphic

display provides the technician an integrated view of test results from which he can perform diagnostic isolation more easily.

2. Control Test Sequence

Another enhancement will be the ability to control the test sequence. Currently, STAMP knows how to control the test sequence, but is unable to do so directly. With today's software configuration control requirements, it is doubtful that the military environment will permit the arbitrary changing of test sequences upon the decision of a software maintenance expert. Some of the maintenance expert rules will, however, enable it to perform what would appear to be an arbitrary resequencing. The rules will dictate which parts of the tests must be executed before others, e.g., initialization. These sequence rules will enable the maintenance expert to control the test-in-progress during diagnostics, which will be especially useful for isolation of intermittents.

3. Analyze Test Results Near Limits

The maintenance expert can have rules to analyze test results which are close to limits of acceptability. The "fuzzy" information that a test result is near a limit is very important for the diagnosis of marginal equipment and intermittents. This information is also useful for prognostics (fault isolation before a hard failure has occurred). The maintenance expert can use its previous diagnostic experience to determine the significance of a result near a limit. If the event is significant, it can be displayed graphically on the screen with color, flashing, shading, etc. Such information should prove invaluable for diagnosing problems that today typically result in RTOK (ReTest OK) and CND (CanNot Duplicate) situations.

4. Analyze Signal Quality Change

The maintenance expert which is in control of the test sequence can sometimes enhance the test by looking at signal quality. This is most easily implemented via the SMART bench approach described there. The ability to monitor signal quality can be used by all of the maintenance experts.

5. After Alarm, Determine when Unit is Again Operating Reliably

The SMART system integrated test can be enhanced to develop rules to determine when a unit is again working reliably after an alarm, thus reducing removals and providing recovery capability after soft faults.

Testability Improvement

To make full use of the capability of the enhanced maintenance experts, the unit under test must have improved built-in testability over that which is typically designed in now. Without improved testability, the maintenance expert will only be able to produce statistical diagnostics e.g., 70% of failures of a node are due to component A, 20% due to component B, etc..

It should also be noted that when future improvement in testability reduces diagnostic ambiguity, there will be a reduced need for self-improving diagnostics.

Benefits

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Maintenance experts can substantially reduce the cost of testing even without direct test observation or learning of diagnostics. Future functional and diagnostic testing based on AI rules reduces costs by:

- o Inclusion of diagnostics automatically with decreased need for re-verification and validation of test programs
- o Reduction in test time due to real modification of test sequences
- o Reducing ATE obsolescence by use of the modular maintenance expert
- o Allowing standardization of operator interfaces and reporting mechanisms
- o Reducing the need for using the bench for diagnosis of fault finding when the ATE cannot be cost effectively used

Battelle: Dr. Pau's Work is Best Surveyed

Dr. Pau's work at Battelle in Switzerland, is clearly far ahead of all other maintenance experts surveyed by this contract. Under internal R&D funding, Dr. Pau has developed 400 metarules for domain independent diagnostics (11). These metarules fall into three classes:

- o Diagnostics through verification
- o Testing while stressing
- o Rules to detect errors of design and interface types

Metarules can be thoroughly tested and then re-used on subsequent systems, greatly reducing the cost for producing a maintenance expert. Dr. Pau has extensively published in this area (see 8.2 - Maintenance Expert) and his 1981 book (15) is the only authoritative treatment of sophisticated diagnosis without the use of artificial intelligence. Dr. Pau's work is shown in the evolutionary chart of maintenance experts (fig. 5.5-1) as the most sophisticated artificial intelligence diagnostics system in current use.

Tangible Tools

人の名の名を名は、 したがないない。 The experience of maintenance expert development at G.E. (8), DEC (9), ICL (10), and with Dr. Pau has shown that it is possible to generate generic maintenance experts which can be inexpensively applied to other systems. Similarly it appears that the hardware of the modular maintenance expert can be developed and used in many test situations. The modular maintenance expert should be usable with very little modification for many of the ATE currently used by the military as well as in new ATE and SMART bench applications.

Maintenance Expert Time Criticality Determines Required Accuracy

A system which requires high availability places high demands for accuracy on a maintenance expert system. For factory or depot testing, a maintenance expert which isolates faults to a single unit 70% of the time is a useful aid. This level of ambiguity is not acceptable, however, for systems where availability is optimized and a quick test after each replacement cannot be performed. Both commercial and military aircraft, for example, require good assurance that the fault is corrected to reduce aborted flights. Figure 5.5-3 indicates that time critical diagnostics must isolate more than 90% of faults in a system so that the maintenance technician will not remove all items in the ambiguity group. This increased accuracy will result from improved inherent testability and not from "self improving diagnostics".

Figure 5.5-3 is based on conversations with technicians from both time critical and non-time critical maintenance organizations testability requirements specifications, and Planetalk magazine which reviews maintenance procedures for commercial aircraft.

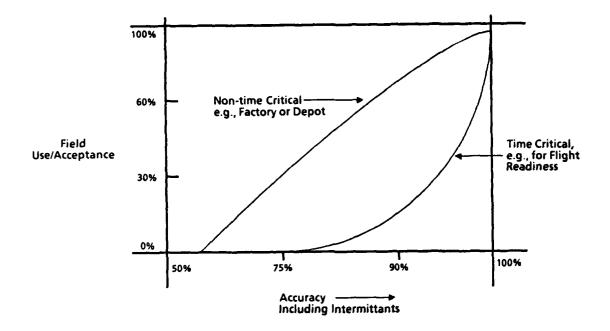


Figure 5.5-3. Maintenance Expert Use Dependent on Time Criticality

Military Maintenance Expert Verification/Validation

There is no evidence of a current verified and validated rule based system used for the military. When rules are generated by an expert for a specific system there is a concern about the correctness and completeness of the rules. The use of system independent rules and/or machine learning from field data will substantially decrease the effort needed to generate each maintenance expert system. Special issues of concern are time varying and noisy data. The first two articles in 8.2 - AI MISC. deal with the role of time in AI. Noisy information is covered by books such as Fuzzy Techniques in Pattern Recognition by A. Kandel. At some point in the evolution of military maintenance expert systems the effects of time and noisy data will have to be considered.

5.6 SMART SYSTEM INTEGRATED TEST

The Smart System Integrated Test (Smart SIT) is very similar to Smart BIT, except that it applies to an entire system, rather than to just a single box of electronics. By intelligent data recording it will reduce fault isolation ambiguity and false alarms, especially for intermittents, either directly or indirectly.

The Integrated Test and Maintenance (1) contract by Boeing studied the use of AI for improved system level testing. While being similar to the Smart BIT concepts, there is generally less time for data analysis in the fighter aircraft environment which was the focus of the ITM contract (table 5.6-1). The use of fault data recording with environmental related information was essential to post-flight analysis that used AI techniques to determine fault cause (see 8.4.3). Smart SIT can provide interactive surveillance of system operation using generic rules for relevant patterns and attributes.

	Preflight	<u>Inflight</u>	<u>Postflight</u>
Establish operational readiness	E	•	
Continual fault monitoring Fault detection (X%)	Ε	E E	E
	E	F	
Support reconfiguration Minimal pilot interface	E.	Ē	
Fault isolation to support reconfiguration	E	E	<u></u>
Fault isolation to LRU (X%)	D(2)	D(1)	£ D(3)
Fault isolation to SRU (X%)	Ε	Ε	D(3)
Maintain system status			
Fault data recording	E	E	E E
Fault record processing			D(7)
Report generation			5(1)
Manual test interaction	E		Ē
Manual isolation			£
Manual bit interrogation			<u> </u>
Automated tech orders	D(5)		D(6)
No additional equipment	Ę	E	D(4)
Aircraft power only	<u> </u>	E	<u> </u>
Intermittent handling	E	E	E
False alarm requirement	E	E	E
Environmental data recording Multiple fault isolation		D(8)	D(9)

E = Essential D(n) = Desirable (rank)

Table 5.6-1. Smart System Integrated Test-Essential or Desirable Capabilities

5.7 COMPARISON OF BOX AND SYSTEM MAINTENANCE EXPERTS

Section 5.5 referred to many box and system level maintenance experts and they are similar in that box and system level both:

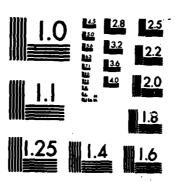
- o Perform offline tests
- o Have no access to Smart BIT
- o Cannot learn

However, system level experts have:

- o More functions to monitor
- o More items to isolate a fault to
- o More organizations to obtain test information from
- o Better functional partitioning (since separate organizations created boxes)
- o Time critical decisions (box removal)

It may be possible to generate a system level maintenance expert for a similar cost as for a box. The fact that the system level can reduce false removals gives it much more benefit than the box maintenance expert. However, as is noted in the evaluation section, a system level maintenance expert requiring high accuracy is too risky in the near term.

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MICROCOPY RESOLUTION TEST CHART NATIONAL BUREAU OF STANDARDS-1963-A

5.8 SMART BENCH TESTING

Brief Description

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The Smart Bench concept developed by Boeing is a method to semiautomate bench testing by use of artificial intelligence, which provides a substitute for manual testing. Smart Bench uses a computer to perform bench tests of electronics. It has the capability of learning both functional and diagnostic information. It also would use the standard instrument interface, the IEEE 488 bus, which enables the computer to control some of the bench test equipment (fig. 5.8-1). Other equipment would remain manually operated. The computer would first "learn" the functional tests that are performed by the human operator with the test equipment. Subsequent functional tests would be performed semiautomatically, with the computer verifying that the test stimuli had been applied, whether by the human or the computer.

Use of a multiplexer switch would enable the computer to measure any two lines of the unit under test, thus allowing confirmation of stimulus and measurement of response. The stimulus can be applied to the unit under test by use of patch cords or already existing Special Test Equipment (STE).

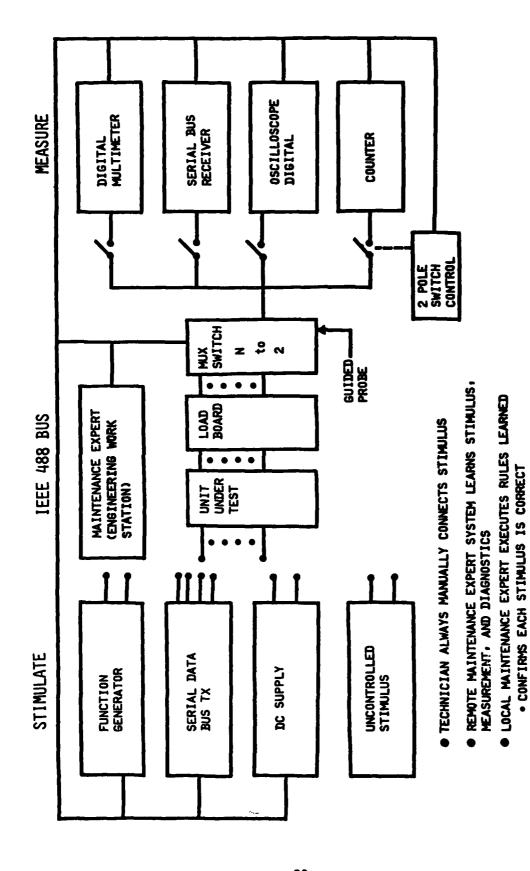
The next stage of the Smart Bench development would include application of incorporation of diagnostic experience through automated learning (IDEAL) previously discussed in section 4.1.

Smart Bench Can Test Units Already in Field

Smart Bench could be used to test either previously fielded units or those of new design. This is one of the few AI testability applications which can be applied to fielded units. It should be especially useful for troublesome units or those where little diagnostic guidance has been provided. In addition, Smart Bench can be used for factory production testing and to aid in the unit design and validation.

Smart Bench Can Test Some Units Which Might Otherwise Be On ATE

Smart Bench can semiautomate bench testing, and can also be used to test units where ATE is not cost effective. Most military testing is performed using ATE, whether ATE or



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Figure 5.8-1 Smart Bench Diagram

• MEASURES AND COMPARES RESULTS
• AIDS DIAGNOSTICS

bench testing is used depends on such factors as number of units to be tested and the length and complexity of test. For those units on the border between ATE and bench, Smart Bench can provide a viable new alternative.

Benefits: Cost Effective Development and Execution of Tests

Smart Bench semiautomatic testing can be developed more cost effectively than ATE or manual bench testing and can execute functional tests more effectively than manual testing. In addition, the capability of Smart Bench to incorporate diagnostic experience will materially decrease the bench maintenance time for all technicians (see figure 4.1-1).

For hardware development programs of low complexity or small volume, it may be possible to use Smart Bench testing for all units.

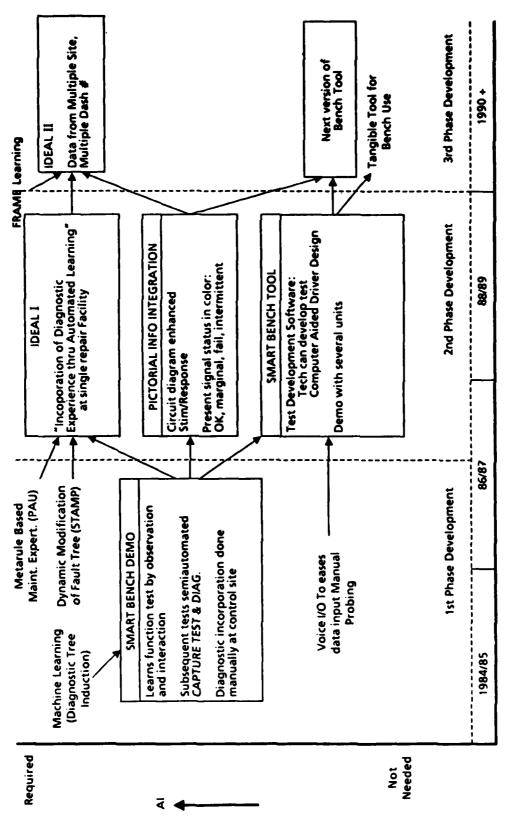
Smart Bench Provides AI Application Test Bed

Smart Bench can provide a test environment for several of the concepts needed by the other AI applications, including Maintenance Experts and Smart BIT. The Smart Bench environment will provide a low cost means to develop the following five concepts:

- o IDEAL
- o Ability to modify fault tree
- o Graphical display
- o Man-machine interactor
- o Semiautomatic testing

IDEAL (Incorporation of Diagnostic Experience through Automated Learning)

IDEAL can be implemented by several different AI and non-AI techniques. Using Smart Bench as a testbed for the AI applications will result in less development risk for the larger AI applications of smart system integrated test and maintenance experts than development of IDEAL using ATE. The Smart Bench evolution figure (5.8-2) projects IDEAL as being incorporated in the second phase of development.



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Figure 5.8-2 Smart Bench Evolution

Ability to modify fault trees (test sequence optimized by observed failures)

Smart Bench could learn to spot the degradations in signal quality, in the same way they would be noticed by technicians familiar with the unit. The signal quality information obtained by IDEAL would be invaluable in diagnosing intermittent units and in reducing the unit specific experience needed by the test technician, thereby reducing training and increasing efficiency.

Integration of information into a graphical display

Smart Bench can provide integrated information graphically to the technician. The information can come from the circuit diagram or via the technical order incorporating stimulus and response data. The status of the unit under test can be shown graphically along with the circuit diagram or functional diagram to indicate if the test was O.K., marginal, failed high or low, intermittent, if the signal was of poor quality, and if a fault was detected, where it was isolated.

Man-machine interaction. (Natural Language, etc.)

Use of voice to improve the man/machine interface capture of information during manual probing will be a useful future (5 year) productivity enhancement. With voice recognition, the technician would not have to record diagnostic experience when his hands are busy with manual probing.

The technology now exists for reading numerical displays; thus, Smart Bench could be enhanced with a TV camera and pattern recognition capabilities to read displays of units under test. The displays to be read could include numeric LED readouts, CRT data indicator lights, etc. (see section 2.7).

Semiautomatic Testing

With Smart Bench, many response measurements will be made without operator intervention. This will result in more consistent and improved testing with fewer units damaged by errors in manual testing. The technician will also have more information for understanding the diagnostics. This should result in reduced frustration and increased employee longevity, thereby reducing training costs.

Smart Bench Can Be Used By Many Projects Without Modification

The capability of Smart Bench at the end of the second stage of evolution can be used by engineers and technicians for developing their own Smart Bench tests with existing bench test equipment. This tool would consist of the Engineering Work Station software and the multiplexer switch shown in the Smart Bench block diagram (fig. 5.8-1). By eliminating the ATE matrix switching capability, and by only having the ability to monitor two channels of responses simultaneously, the cost of the Smart Bench system is only one tenth to one hundredth that of an ATE system. This is offset by the increased personnel costs due to slower tests.

Development Status

Smart Bench is a concept developed by Boeing that has not yet been implemented. While not producing overall large cost savings, it can provide a means to prototype maintenance expert concepts.

Risk

Smart Bench, as proposed, uses established AI techniques that have been proven in other applications. For that reason there is little risk in the application of machine learning and rule based expert systems to this bench environment.

5.9 AUTOMATIC TEST PROGRAM GENERATION (ATPG)

Summary

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- o AI is being applied to Digital ATPG
- o The opportunity for savings is low due to a segmented market

ATPG is used to create ATE functional tests for digital, analog and computer based cards and boxes. It uses simulation capability on a large computer (often a VAX) to automatically generate these electrical tests and is frequently used for testing of digital electronics for both commercial and military electronics (see book, Bennetts, "Introduction to Digital Board Testing", 1982).

Benefits of AI

Robinson (33) states that AI would:

- o Produce well structured tests
- o Produce tests more quickly by using hierarchical functional knowledge
- o Be extensible

A block diagram of Robinson's test generator is shown in figure 5.9-1. A very large ATE manufacture (Gen Rad) is funding the work primarily for digital electronics. It is doubtful that much improvement in coverage of digital functional tests is expected, as that is limited by the amount of DFT (fig. 3.2-2).

Analog ATPG (AATPG) with AI is the focus of a 5 year Navy R&D plan for the mid 1980's. There has been very little success with analog ATPG without AI, due in part to a defocussed and decreasing market. The over 40 dialects of the ATLAS language required for military analog ATE tests coupled with lack of standard ATE and decreasing use of analog electronics makes for a small market for an AATPG.

The main impact of AI on ATPG will probably be the insertion of functional circuit knowledge into the simulation. Presently both analog and digital circuits are simulated at a very low level that does not include knowledge of the circuit function. Tests are not

well structured and cannot be quickly simulated if they try to test all possible functions of a circuit rather than testing the function designed for.

Limited Opportunity for Cost Savings

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When compared with the other AI opportunities evaluted, ATPG is not seen as having as many benefits. It does not:

- o Improve testability
- o Decrease test false alarms, etc.
- o Decrease test time significantly

Self Test Capability Decreases Need for ATPG

The increasing capability of new units under test should permit increasing use of BIT. Functional BIT capability in excess of 95% is being required of new military electronics, which should decrease the ATE ATPG requirements. Increasing use of VLSI with self-test capability will have a similar effect on ATPG.

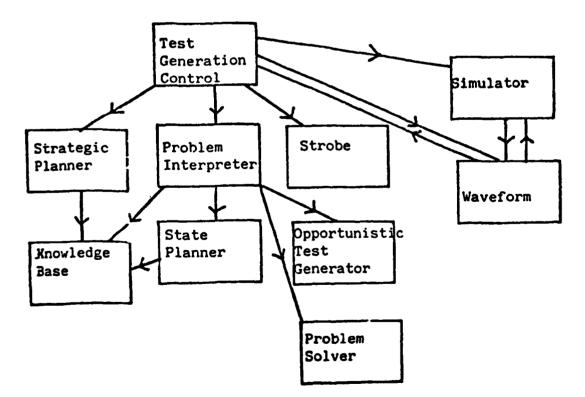


Figure 5.9-1 HITEST Test Generator - Block Diagram

5.10 REQUIREMENTS FOR DEVELOPMENT AND USE OF AI APPLICATIONS

A typical government research and development effort will not result in a product that can be directly used by contractors. To maximize the cost effectiveness of the AI opportunities it is desirable to have all developers and end users of the applications make use of the same hardware and software. This would permit a synergistic sharing of development techniques and application information.

Industry standardization of engineering work stations is providing a breakthrough in low cost development and widespread use of AI opportunities. Compatible machines will soon be directly available to designers and developers.

Developers Need AI Language and Graphics

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The developers of the AI techniques need a machine that can execute an AI language such as LISP or PROLOG. They also need a high resolution graphics display for their own program development and as a means to display diagrammatic maintenance information such as a circuit. Often, when the developers have optimized the machine for their own needs they have selected machines designed to directly execute an AI language such as models by Xerox, LMI, or Symbolics. While this does offer faster execution of an AI language to ease development tasks the AI language still does not execute fast enough for a majority of AI applications. Because of that, it must later be re-coded in a procedural language (typically Pascal), and re-hosted on another machine.

Product-Designers Need Industry Standards

The product designers among contractors and subcontractors want tools that can be used without having to buy new equipment or having to rehost the tools to their own equipment, which results in a long term software maintenance burden. Industry standards result in multiple sources of compatible hardware and software. Sole source systems, such as the LISP language AI machines, are not cost effective as corporate standards for long term operation, so they will not be widely available in a company.

There are currently three standard low to medium cost computers widely used by the aerospace contractors: the DEC, VAX family (medium cost), IBM PC (very low cost), and the emerging low cost engineering work stations, (with the Apollo and Daisy based

systems having the majority of the market, Electronics, May 17, 1984). Several expert systems have been developed, notably by General Electric (8) and D. R. Michalski (18). These were developed on a VAX and then executed on an IBM PC; however, both of these computers lack the good, standard, high resolution graphics which are of great value in a design or maintenance application. The engineering work station is able to supply the power of a VAX processor to a single user and include standard higher resolution graphics. The engineering work station is now an excellent host for testability expert systems. Table 5.10-1 provides a comparison of the machine approaches just discussed in terms of whether the machine meets AI application to testability development and application needs.

				USED BY
	SPEED	CAPACITY	GRAPHICS	DESIGNERS
LISP Machines	Yes	Yes	Yes	No
IBM PC	No	No	OK	Yes
VAX	Yes	Yes	No Standard	Yes
Eng. Work Station	OK	Yes	Yes	Yes

Table 5.10-1 Computer Attributes

Depot Maintenance Needs Connection to ATE

Maintenance expert system applications described in this report initially need to monitor ATE operation, but will evolve into controlling ATE operation. While it is possible to conceive of designing new ATE with integral AI capability, it is much more feasible to have the AI function added to the front of an existing ATE.

The Smart Bench and the ATE application both need a small modular computer with circuit knowledge, good graphics, and a means to record diagnostic information.

Engineering Work Station Provides Cost Effective Testability

The engineering work station provides a breakthrough in cost effectiveness by being able to provide a design tool with capability that exceeds that available on mainframes just a few years ago. It provides a single host which satisfies the needs of developers, product developers, and end users. As shown in table 5.10-2, it also provides the AI language

needed during initial development, and the procedural language needed for high speed execution, as well as circuit modeling capability, high resolution graphics, etc.

	LISP MACHINE	EWS 1984/85	AI/T REQUIRES
USE BY DESIGNERS			
IC DESIGN			
MICROPROCESSOR PROGRAMMING			
CARD DESIGN'			Functional
BOX DESIGN			Functional
HIERARCHICAL MODELING			
SYSTEM SIMULATION			
TESTABILITY AUDIT			
INTEGRATE HW/SW MODEL			
GRAPHICS - HIGH RESOLUTION	0.00		
LANGUAGES - LISP, PROLOG C, FORTRAN, PASCAL		1	100 mg/s
PROJECT MANAGEMENT			

Capability

None





Table 5.10-2
Engineering Work Station (EWS) Will Meet Testability Application Requirements by 1985

The technological progress made by semiconductor technology has provided in the engineering work station an interactive system which is big enough, fast enough and cheap enough to be really useful in a wide range of applications. This single user computer does not need to communicate with any other machine to perform its tasks, and gives the designer more net productivity than he usually has with the shared VAX computer. There are overviews of engineering work stations in the April 84 issue of IEEE Computer Graphics and Applications, which includes a description of the Apollo Domain system. The same magazine in Dec 1983 describes the Mentor Graphics system in an article entitled, "Tools for Computer-Aided Engineering," by T. Bruggere. Further work station references are in the CAD part of section 8.2.

It is interesting to note that while semiconductor technology has increased unit complexity and thus been the cause of testability problems, semiconductor technology has also made it possible for engineering work stations to be able to cure the testability problems (see figure 5.10-1).

Standard Hosts Can Be Used Throughout Most Applications

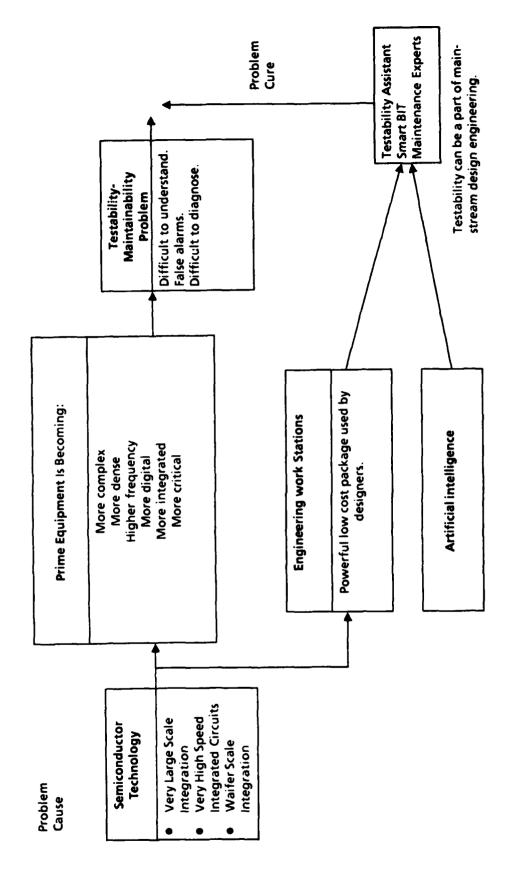
Standard computers and standard knowledge bases can be used throughout all phases of all the applications evaluated. While the AI techniques can be put on an assortment of general purpose computers or special purpose LISP machines, the sharing of development results among the applications is the most important factor and will produce large savings in time and money.

In each of the evaluated opportunities there are three types of groups involved:

- 1) Research and Development
- 2) Product Designers who configure product to their project
- 3) Product users

Substantial savings can be realized whenever a single application can use standard hardware and software for all three groups. The cost of rehosting an AI application for each user (subcontractor) would otherwise inhibit its extensive use. It should be noted that the cost for some engineering work stations will drop below \$10,000 in 1984. The low hardware cost should be an incentive for standardization.

As of 1983, in excess of 50 manyears of work has gone into software tools to be used on engineering work stations like the Mentor Graphics systems, which are needed by AI applications to testability. It takes many manyears of work to develop real circuit modeling tools, much less the hierarchical interrelationships which are needed for more complex designs. The LISP machines offer virtually no support of electronics concepts. The AI application candidates being evaluated by this study were each examined on their potential use of engineering work stations; the results are presented in table 5.10-3.



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FIGURE 5.10-1 Semiconductor Technology Causes and Cures Testability Problems

Table 5.10-3 Engineering Work Stations (EWS) Used by All Applications in Many Phases

APPLICATION		PHASE								
		CONFIGURE PRODUCT								
	R&D	TO PROJECT	USER							
CAPDT	EWS	EWS	EWS							
SMART Bit	EWS	EWS	EWS used to analyze and							
			program it							
Maint. Expert-BOX	EWS	EWS	EWS controls ATE							
SMART SIT	EWS	EWS	Uses militarized CPU							
SMART Bench	EWS	EWS	EWS							
ATPG	EWS	EWS	EWS							

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Maintenance Experts Can Use Functional Circuit Information On Work Station

While the maintenance expert systems analyzed by this report do not claim any knowledge of circuit function, and so cannot be used for card level diagnosis, a future marriage of AI circuit descriptions with the engineering work stations may provide this capability. The engineering work station could also interactively simulate possible faults in a circuit to aid in diagnosis of faults other than the single, stuck at "0" or "1" type of fault usually modeled. Other non-AI tools like reliability and maintainability analysis will probably also be added to the CAPDT on the engineering work station, as they have many of the same concerns and data.

6.0 EVALUATION OF OPPORTUNITIES

Summary

The evaluation of the AI opportunities is presented in two stages. In the first stage, an evaluation matrix details the life cycle costs or savings at each phase of development for the application opportunities identified in Section 5.0. Because a system level application results in much higher life cycle cost leverage, the cost evaluation uses a weighting for systems level applications several times that of box or card level opportunities; a factor of ten was chosen as a first approximation based on the potential cost leverage of an improvement to a system over a box or card. AI opportunities were ranked on the basis of estimated life cycle cost reduction provided, from greatest to least:

	% Reduction
Maintenance Expert System - Smart	6.4
Smart System Integrated Test	6.3
Computer Aided Preliminary Design for Testability	6.2
Maintenance Expert - System	3.7
Smart Bit	0.6
Smart Bench	0.4
Maintenance Expert - Box	0.4
Automatic Test Program Generation - Analog	0.2
Digital Automatic Test Program Generation	0.2

Weighted values based on the following criteria were then added to the life cycle cost evaluation to arrive at a figure of merit for each application:

- o Risk of Demonstration in 3 Years
- o Development Status
- o Cost to Obtain Demonstrated Product
- o Cost to Develop Tool
- o Usefulness of Resulting Tool
- o Retrofit Capability
- o Payoff Leverage (Benefit/Cost)
- o Mission Critical Function
- o Enabling Technology

The figures of merit were separated into three categories ("1" being high), with at least a 4 point gap between the high, medium, and low recommendations

Category	Application
1	Computer Aided Preliminary Design for Testability
2	Maintenance Expert - System
	Smart Bit
	Smart System Integrated Test
	Maintenance Expert - Smart
	Maintenance Expert - Box
3	Smart Bench
	Digital Automatic Program Gen. with Machine Learning
	Automatic Test Program Generation - Analog

6.1 LIFE CYCLE COST EVALUATION

This section uses a matrix format to evaluate the life cycle costs and benefits for each application opportunity separately. Seven evaluation criteria were used and each AI application evaluated for impact on the seven phases of a product's life cycle. Discussion of the terms used in the evaluation matrix are presented first.

6.1.1 LCC Evaluation Criteria

The following seven criteria assess the impact on testability problems and were used as testability factors in the evaluation of the opportunities:

- o Test Time Reduced
- o Hard Fault Detection
- o Hard Fault Isolation
- o Intermittent Discrimination & Isolation
- o False Alarm Reduction
- o Experience Level Reduced
- o Reduced Removals

Test Time Reduced

Many test programs must run through the entire test sequence every time, while providing the technician with no capability to make gross tests of entire sections, loop on a particular test sequence, or slowly accumulate test information to diagnose intermittents. The use of maintenance expert systems is not necessary to make the testing more flexible and hierarchical, but their incorporation produces this effect. A reduction in test time benefits LCC by increased utilization of test equipment and the test technicians for ATE, bench and systems tests. Large benefits in this area could also result in fewer ATE systems being required at large depot repair sites.

Hard Fault Detection

At every level of testing it is desirable to have the best fault detection coverage for hard faults possible. This is relatively easy for digital circuits, but is much more difficult for circuits or systems which have poor DFT, use analog circuits or microprocessors. Improving testability during the design phase of the electronics provides the greatest benefit for the effort expended, because improved fault detection in the unit has greater LCC benefits than improved fault detection solely based on ATE. As shown in Figure 3.2-3, only by improving testability is it possible to detect all hard faults.

Hard Fault Isolation

Because it is a more difficult task and a less mature capability, there is more opportunity for improvement in hard fault isolation than in their detection. Both can be improved through the use of DFT techniques and by a maintenance expert system that can learn the isolation strategies for real world faults. However, it takes a greater level of DFT to locate a fault inside a complex network than to detect a fault at its output (see section 4.2).

Intermittent Discrimination & Isolation

Intermittent discrimination and isolation is an immature field which could provide benefits to many types of systems. The test system must allow a fuzzy description of the state of a circuit (i.e., a description covering a range of states: good, most likely good—may have suspected as intermittent, degrading-but-not-yet-bad, and bad). Products

which accumulate information about an item's marginally bad performance during the time it is running provide much more help in detecting and isolating intermittents than a single slow test of performance on an ATE system. That approach also provides the basic capability needed to discriminate between intermittents and false alarms. (1)

False Alarms Reduced

Causes of false alarms are most easily eliminated using CAD tools to help reduce false alarm causes through better designs. CAD can provide the ability to simulate full system operation with BIT and software running and to simulate various hard and soft faults. The simulation results interpreted by the designer allow him to find and then eliminate many of the causes of false alarms. Additionally, methods to acquire and record fault information during circuit and system debug (in full scale development), will find many real world/environmental causes of false alarms. This information is most easily acquired by some form of BIT that has non-volatile memory. After it's fielded, hardware becomes virtually unalterable; however, the BIT test software can still be changed (under configuration control). Smart BIT with reprogrammable features allows experimentation with proposed modifications and would also ease their incorporation.

Experience Level Reduced

Much of commercial and military electronic testing has gone from bench to ATE so as to increase the reliability of testing and to reduce test time. The military ATE software, however, has greatly limited the technician in what he can do. The technician is rarely able to modify the test sequence or test limits to diagnose a problem. As circuits become more complicated, especially microprocessors, there tends to be little or no information available to the test technician on their operation. ATE have also become very complex to operate and each one is different. It now requires 6 to 12 months of training for technicians to become familiar with operations of complex ATE, and learn how to compensate for its limitations to perform the testing and diagnosis required.

Skill level reduction is, based on the reality of military service experience, better expressed as "experience level reduction." Because of this, it has been the conclusion in segments of the military community (42) that ATE should be changed so as to require less training for use in performing maintenance. As a corollary we believe that the ATE must be configured to work with the technician, rather than just having him serve as a button

pusher. Instead of having a computer guided probe, where the technician is told where to place a probe so that the computer can make a test, there should be interactive diagnosis where both the human and the computer can suggest areas of the circuit to be tested. This is already being done with sophisticated software (non-AI) in some commercial card testing ATE, such as that manufactured by Fairchild (Series 70).

The best product for "skill level reduction", (actually productivity improvement using short-time staff), would be a standard human interface for ATE which would allow interaction with the test in progress. By providing an identical user interface for different ATE, it would also be easier to reassign technicians.

Reduce Removals

Removing an item from a system causes a whole chain of costly actions to occur. Many authors address the need to reduce removals, but the following reference also includes quantitive evaluations:

"... Field maintenance data (exists) showing that 40% of the avionics equipment removed from an aircraft is fault free and fully capable of satisfying its assigned mission function. This inability to identify malfunctioning equipment without ambiguity results in a 67% workload increase at organizational and intermediate maintenance levels." - Top down built-in test architecture study, L.R. 523, Lockheed, April 1980.

Using better DFT to provide less isolation ambiguity reduces removals directly. Similarly, recording actual fault data can provide knowledge to technicians to allow their diagnostic experience to grow, provided that data can be made available to them in a meaningful and timely manner.

6.1.2 Life Cycle Phases

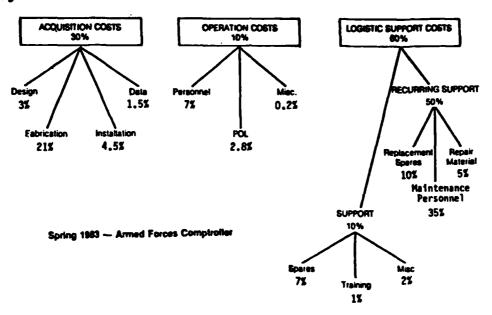


Figure 6.1-1 Distribution of Life Cycle Cost

The following table showing percentage of total life cycle cost for the identified subfactors was derived from figure 6.1-1. These numbers will serve as primary inputs in the evaluation.

Table 6.1-1 Life Cycle Cost Distribution

0	Design	3%
0	Fabrication	21%
0	Operations Personnel	7%
0	Support Spares	7%
0	Replacement Spares	10%
0	Maintenanace Personnel	35%
0	Replacement Material	5%

Design

Designers are often not aware that the design phase is typically only 3% of the total life cycle cost. Frequently they optimize testing for their own requirements, ignoring field types of faults and minimizing board area allocated to testing. Required use of testability

tools and standards will aid and force the insertion of testability into the design phase and increase designer awareness.

Fabrication

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Al applications can produce benefits in fabrication by reducing fault isolation time and by improving fault detection coverage. The test time is not as much a concern as the isolation time since fault isolation is frequently made away from the ATE. Improvement in inherent testability of the IC, card, box, or system all reduce fabrication costs. Without a high level of inherent testability, faults can pass undetected, and result in expensive rework.

Inherent testability improvement will also reduce costs associated with Automatic Test Program Generation (ATPG), Test Program Sets (TPS), and engineering debugging at all levels. During this program phase, AI applications can also support an aggressive program of false alarm and intermittent reduction by design changes and modifications to the BIT and system integrated test (SIT) that result from capture and analysis of faults during the intensive testing that early production run articles are subjected to.

Operations Personnel Costs

The largest benefits in Operations Personnel Costs wil be achieved through improvement of intermittent isolation and by reduction in false alarm rate because intermittents and false alarms greatly complicate and extend the tasks required of the operations personnel. The benefits of hard fault ambiguity reduction are of less concern. The effect of removing two boxes due to poor fault isolation capability is not felt at this stage, but rather at phases downstream in the logistics and maintenance system.

Support Spares

Support spares are those units purchased initially for the system for support and maintenance facilities and to fill the logistics pipeline. Fewer spares need to be purchased initially for a system if it is known that there will be fewer removals caused by false alarms and intermittents due to improved diagnostic capability.

Replacement Spares

Replacement spares include cards and boxes purchased to replace the support spares broken or else destroyed during tests, as well as those spares needed to replace units with undiagnosable problems of both a hard and intermittent nature. Improving fault isolation capability will decrease the requirement for replacement spares. Improved fault isolation also reduces the number of units destroyed during test due to "shotgun" methods of component replacement as an isolation technique. It is Boeing's experience that with five or more layers in a printed wiring board there is a 50% chance of a layer interconnection being destroyed if the same component is removed twice.

Maintenance Personnel

The largest factor affecting a reduction in ATE maintenance personnel cost is the reduction in field removals. If units are not removed, they need not be tested, thus reducing personnel requirements.

Repair Material

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The factors effecting repair material are the same as that for replacement spares, except that decreasing intermittents and false alarms will not significantly decrease repair material. While a false alarm can force the replacement of a box, it usually will not cause a component to be removed from a board since causes of false alarms are usually of a higher level than the component.

6.1.3 LCC Evaluation Results

The AI applications of section 5.0 to be evaluated are:

- o Computer Aided Preliminary Design for Testability—CAPDT would be a testability assistant directly available during preliminary design phases.
- Smart Built-In Test—Smart BIT used in boxes or cards can identify intermittent faults and reduce false alarms.
- Smart System Integrated Test—Smart SIT is a system level Smart BIT which performs testing while the system is operating.
- Maintenance Expert Box-ME BOX provides offline test management with self improvement of functional tests.

- o Maintenance Expert System—ME SYS describes the kind of capability that can be expected during the next three years.
- o Maintenance Expert—Smart—ME Smart incorporates the benefits/risks in the 3 to 5 year time period, of including learning capability in the maintenance expert system and its ability to access to Smart BIT information.
- o Analog Automatic Test Program Generation—ATPG-ANA would be able to understand circuit functional operation.

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- o Smart Bench is a maintenance expert system developed for use with bench test equipment controlled by an engineering workstation.
- o Digital Automatic Test Program Generation with Machine Learning—DATPG WML learns refinements by test engineer to DATPG as a result of experience.

Estimates were made of the benefit of each AI application to the testability factors in Table 6.1-2. The maximum benefit is indicated with a 10 (example: Smart Bit Benefit to Intermittent Isolation) and the least benefit by a zero (example: ATPG-analog effect on false alarm reduction).

Table 6.1-2 Testability Benefits of Opportunity

TESTABILITY FACTOR	CAPD	SMART	SMART	ME	ME	ME	ATPG	SMART	DATG
	TEST	BIT	SIT	BOX	SYS	SMART	ANA	BENCH	W ML
TEST TIME REDUCED	7	8	6	7	9	8	2	7	2
HARD FAULT DETECTION	9	7	3	5	5	5	4	3	3
HARD FAULT ISOLATION	8	5	5	5	2	6	4	5	3
INTERMITTENT ISOLATION	9	10	9	4	2	9	0	5	2
FALSE ALARMS REDUCED	4	9	9	2	2	9	8	2	2
EXPERIENCE LEVEL REDUCED	5	8	8	8	10	10	8	8	2
REDUCE REMOVALS	8	8	10	3	6	8	3	3	3

Next, the benefit (or cost) of testability factors in each life cycle phase was established (Table 6.1-3). The benefits range from -1 to +3, where -1 indicates a net cost during that phase, a 0 indicates no LCC benefit and +1, +2 and +3 succeedingly increasing benefit.

Table 6.1-3 Benefit of Testability Factor in Each Life Cycle Phase

	TEST	HARD	HARD	INTERM	FALSE	EXPER	REDUCE	ROH
	TIME	FAULT	FAULT	ISOLATE	ALARMS	LEVEL	REMOVAL	HEIGHT
	REDUCED	DETECT	ISOLATE		REDUCED	REDUCED		
DESIGN	9	6	-1	-1	-1	•	•	-3
FABRICATION	1	1	1	1	0	•	6	4
OPER. PERSONNEL		0	1	2	2	9	1	6
SUPPORT SPARES	0	8	2	0	0	•	2	4
REPLACE SPARES	8	9	1	3	2	•	1	7
MAINT. PERSONNEL	1	0	1	1	1	1	3	8
REPAIR MATERIAL	•	8	1	8	•	•	1	2

The next step of the evaluation consists of multiplying these two matrices (6.1-2, 6.1-3) (column-by-row) to obtain the benefit of each application to each life cycle cost phase. The results are shown in Table 6.1-4. For example, to get "33" for a "Fabrication" benefit for "CAPD Test," the "Fab" row of table 6.1-3 is multiplied by the "CAPD Test" column in table 6.1-2 item-by-item. So, the first four lines are multiplied by "1", the last three lines by "0". Summing the digits: 7+9+8+9 = 33. This process is repeated for each matrix position to obtain table 6.1-4.

Table 6.1-4 Weighted Benefit

	CAPD	SMART	SHART	ME	ME	ME	ATPG	SMART	DATG
	TEST	BIT	SIT	BOX	SYS	SMART	ANA	BENCH	H ML
DESIGN	-21	-24	-23	-11	-6	-24	-4	-12	-7
FABRICATION	33	30	23	21	18	28	10	20	10
OPERATIONS PERSONNEL	42	51	51	28	16	56	7	22	14
SUPPORT SPARES	32	26	30	16	16	28	14	16	12
REPLACE SPARES	51	61	60	24	18	59	7	27	16
MAINTENANCE PERSONNEL	57	64	67	35	43	66	23	36	20
REPAIR MAT'L	16	13	15	8	8	14	7	8	6

The next matrix (6.1-5) is a normalization of the weighted benefits shown in Table 6.1-4. This eliminates the total weight bias (sum of column weights) from each column of Table 6.1-3. To do this, each number of a row is divided by the total weight of that same LCC phase that was __mmed at the end of its row in Table 6.1-3. If the weighting had been expressed as percentages normalization step would not have been necessary.

Table 6.1-5 Normalized Benefit

	CAPD TEST	SHART BIT	SMART SIT	ME BOX	ME Sys	ME Smart	ATPG ANA	SMART BENCH	DATG W ML
DESIGN	-7.00	-8.00	-7.67	-3.67	-2.88	-8.88	-1.33	-4.88	-2.33
FABRICATION	8.25	7.50	5.75	5.25	4.50	7.00	2.50	5.88	2.50
OPERATIONS PERSONNEL	7.00	8.50	8.50	3.33	2.67	8.33	1.17	3.67	2.33
SUPPORT SPARES	8.00	6.50	7.50	4.00	4.00	7.00	3.50	4.80	3.00
REPLACE SPARES	7.29	8.71	8.57	3.43	2.57	8.43	1.60	3.86	2.29
MAINTENANCE PERSONNEL	7.13	8.00	8.38	4.38	5.38	8.25	2.88	4.50	2.50
REPAIR MAT'L	8.88	6.50	7.50	4.88	4.88	7.00	3.50	4.88	3.00

To obtain the potential percentage of LCC reduction for each application, as shown in Table 6.1-6, each item in a row of Table 6.1-5 is scalar multiplied by its corresponding LCC distribution percentage listed in Table 6.1-1. These percentages are then summed to get the percent LCC reduction per application.

Table 6.1-6 Percentage LCC Reduction

	CAPD TEST	SMART BIT	SMART SIT	ME BOX	ME SYS	ME SMART		SMART BENCH	DATG W ML
DESIGN	21	24	23	11	06	24	84	12	87
FABRICATION	1.73	1.58	1.21	1.10	.95	1.47	.53	1.05	.53
OPERATIONS PERSONNEL	.49	. 68	.60	.23	. 19	.58	.08	.26	.16
SUPPORT SPARES	.56	.46	.53	.28	.28	.49	.25	.28	.21
REPLACE SPARES	.73	.87	.86	.34	.26	.84	. 10	.39	.23
MAINTENANCE PERSONNEL	2.49	2.80	2.93	1.53	1.88	2.89	1.01	1.58	.88
REPAIR MAT'L	.40	.33	.38	.20	.20	.35	. 18	.20	. 15
% LCC REDUCTION/APPLIC	6.19	6.38	6.26	3.58	3.69	6.38	2.89	3.63	2.08
EFFECT OF APPLIC ON SYS	1.00	. 16	1.00	. 10	1.00	1.00	. 10	. 10	. 10
% SYSTEM LCC REDUCTION	6.19	.64	6.26	.36	·3.69	6.38	.21	.36	.21

6.2 TOTAL EVALUATION OF OPPORTUNITIES

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Ten parameters are used to assess the risk, cost, and benefits of each of the AI opportunities to determine a total evaluation. Table 6.2-1 shows each parameter with its range and weight (importance) along with this study's evaluation of each of the described AI applications for each parameter. Table 6.2-2 incorporates the parameter weights into each evaluation (by multiplication of every item by its associated parameter weight). Those parameters which reduce the figure of merit have weights which are negative. A sum of the weighted values for each application is then made to find its figure of merit.

Risk Demo 3 year: This is the risk of being able to complete a demonstration project by 1987. High risk is generally due to lack of research that can be directly used and is shown by a high numerical evaluation (note the negative multiplier). "Smart" SIT and maintenance expert approaches, as can be seen on evaluation charts, are risky for this time frame but will be less risky after 5 years.

<u>Development Status:</u> Applications which have commercially available products are rated as 3. Prototyped applications are rated as a 2, while those with ongoing experimentation/research are given a one. Mere concepts are rated as a zero.

Cost to Demonstrate Product: This is the estimated number of manyears necessary for a contractor to make a demonstration of the application. The evaluation quantities are based on similar recommendations in AI Applications to Maintenance (3). Note though, that the mere demonstration of an application does not ensure it widespread, timely incorporation. Factors influencing this were discussed in section 5.2.

Cost to Develop Tool: Ten to thirty man-years are typically necessary to develop a general purpose tool which can be easily rehosted. All applications are in this range except for the Smart System level maintenance expert, which is more complex than average.

<u>Useful Tool is a Result:</u> Will the AI technique be easily rehosted and used by contractors and subcontractors once it is developed? The best techniques can be directly used by designers and technicians. Low ratings are given to systems which require specialists and much new rule generation.

Table 6.2-1 Unweighted Evaluation

	RANGE	wt	CAPD TEST	SMART BIT	SMART SIT	ME BOX	ME SYS	ME SHART		SHART BENCH	DATG H HL
RISK DEMO 3 YEAR	6-5	-1	2	3	5		•	5	5	3	5
DEVELOPMENT STATUS	8 +3	1	•	1	1	3	2	1	1	•	•
COST TO DEMO PRODUCT	MYEAR	3	5	3	8	2	2	5	5	3	3
COST TO DEVELOP TOOL	MYEAR	2	36	10	28	26	20	40	30	30	10
USEFUL TOOL IS A RESULT	6-5	1	5	4	8	3	3	3	3	5	3
RETROFIT CAPABILITY	9-5	.3	•	3	2	2	1	1	1	5	ŧ
PAYOFF LEVERAGE (BEN/COST)	20	X .5	5	•	•	•	•	5	•	5	•
MISSION CRITIAL FUNCT	9-5	1	3	3	5	1	2	4	1	1	,
ENABLING TECHNOLOGY	6-5	.5	5	5	3	8				8	•
LCC REDUCTION - SYSTEM	%	1.5	6.19	.64	6.26	.36	3.69	6.38	.21	.36	.21

Table 6.2-2 Weighted Evaluation

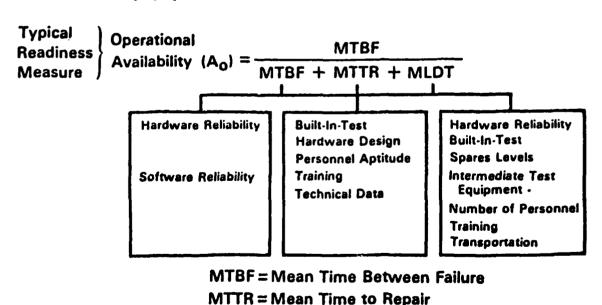
SUBTOTAL OF WIX PARAMETRIC	CAPD	SMART	SMART	ME	ME	ME	ATPG	SMART	DATG
	TEST	BIT	SIT	80X	SYS	SHART	ANA	BENCH	H ML
RISK DEMO 3 YEAR	-2	-3	-5			-5	-5	-3	-5
DEVELOPMENT STATUS		1	1	3	2	1	1		•
COST TO DEMO PRODUCT	-1.5	9	-2.4	6	6	-1.5	-1.5	9	9
COST TO DEVELOP TOOL	-6	-2	-4	-4	-4	-8	-6	-6	-2
USEFUL TOOL IS A RESULT	5	4		3	3	3	3	5	3
RETROFIT CAPABILITY		.9	.6	.6	.3	.3	.3	1.5	.3
PAYOFF LEVERAGE (BEN/COST)	2.5	0	0		8	2.5	•	2.5	•
MISSION CRITIAL FUNCT	3	3	5	1	2	4	1	1	1
ENABLING TECHNOLOGY	2.5	2.5	1.5				8		•
LCC REDUCTION - SYSTEM	9.3	1	9.4	.5	5.5	9.6	.3	.5	.3
FOM = SIM WEIGHTED PARAMETERS	12 8	4 5	4 (2 5	9 2	4 0	_4 0		-2 2

Retrofit Capability: High ratings are given to techniques which can be cost effectively applied to already fielded systems. Smart Bench can be applied with no modification to fielded units. Smart BIT can be used in the retrofit of existing BIT systems since its chip set would require little room and its ability to record faults would not require any new system or logistics capability.

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Payoff Leverage: Any application that has a potentially high payoff (benefits more than 20x the development cost) is given additional weight. As a first approximation, a weight of 5 was chosen to indicate that the 20x threshold is met or exceeded by an application.

Mission Critical Function: Is the system able to perform its mission when called upon? If the system is unavailable due to maintenance, readiness is decreased. The worst case situation comes during a war time situation. Maintenance actions of 4 hours which are normally accepted during peacetime operation may be considerably lengthened in a high sortie generation schedule. An application is able to help a system perform its mission well (a rating of 5) if it provides a high level of self test and has a future capability to perform prognostics, all while assuring a low rate of Retest OK for removed boxes. Figure 6.2-1 shows some of the factors that determine readiness from Meth's article in the Proceedings of the Reliability & Maintainability Symp. 1984. (47)



MLDT = Mean Logistics Downtime

Figure 6.2-1 Factors That Effect Weapon System Readiness (47)

<u>Enabling Technology</u>: Those applications that are going to be essential to broad reductions in testability problems in the near term are given a rating of 5, important applications are given a 3.

LCC Reduction: The data from Table 6.1-6 is used here.

FIGURE OF MERIT

The bottom line of table 6.2-2 is the figure of merit for each application evaluated. It is a balance between the large negative factors of risk of demonstration in 3 years and cost to develop a tool, against the substantial positive weights given to having a tool and the amount of life cycle cost reduction. Figures of merit with a range from 12.8 to -6.9 were separated into three categories, with at least a 4 point gap between the high, medium, and low recommendations.

Category	FOM	Application
1	12.8	Computer Aided Preliminary Design For Testability
2	8.2	Maintenance Expert - System
	6.5	Smart BIT
	6.1	Smart System Integrated Test
	5.9	Maintenance Expert - Smart
	3.5	Maintenance Expert - Box
3	.6	Smart Bench
	-3.3	Digital Automatic Program Gen. with Machine Learning
	-6.9	Automatic Test Program Generation - Analog

Category 1 represents the highest level of recommendation; it's practical, it has large benefits. Category 2 represents some excellent candidate applications, but each has some shortcoming that either makes it more risky or is of a lesser benefit, based on cost. Category 3 items provide insufficient benefit for their cost to be considered. These ratings and other more intangable factors, that influence the acceptability of an approach are discussed further in Section 7.0, Study Findings and Recommendations.

7.0 STUDY FINDINGS AND RECOMMENDATIONS

This study provides the foundation for a logical and cost-effective program to apply artificial intelligence to testability. Emphasis was on those artificial intelligence (AI) techniques capable of practical application to testability problems immediately or with low-risk development within three to five years.

It was shown in this study that cost effective testability techniques for use in electronic systems can utilize artificial intelligence techniques. Testability problems addressed include reducing false alarms, isolating intermittent failures, assuring adequate failure coverage by Built-In Test and Automatic Test Equipment (BIT/ATE) and reducing maintenance training requirements. In addition, these techniques should be capable of reducing life cycle costs by approximately 5% by reducing testing costs, which account for more than 20% of LCC.

It was determined that the most cost effective approach to development and use of application tools to develop diagnostic rules which are system independent (metarules). It was recommended that this approach be used for any development program applying an expert system to testability. It was also recommended that new development in applying AI to testability use standard engineering work stations as the engineer's development tool because the aerospace industry is now racing toward massive use of engineering work stations in its design organizations. Also, AI languages such as LISP and PROLOG should also be available shortly on the work stations.

This section consolidates and presents a detailed discussion of the fundings and recommendations of this study.

7.1 STUDY FINDINGS

The study findings described in this section are arranged in the same order as this study report for ease of reference. These include findings in the following areas:

- o AI techniques
- o ATE/BIT applications
- o Testability applications
- o Al solutions to testability problems
- o General findings

7.1.1 AI TECHNIQUE FINDINGS

Expert system development is the most active area in artificial intelligence. These systems are now capable of being used as knowledge managers with several testability applications.

Diagnostic metarules and machine learning will allow maintenance expert system tools to be developed that can be easily applied to many projects. Presently, most expert systems are developed through the knowledge engineering lifecycle for each project with the knowledge coming from a single human expert. A few maintenance expert system tools have been created (8, 9), including some that can incorporate diagnostic experience (10,11). The use of system independent, diagnostic metarules will permit a maintenance expert system to be created much more economically than those previously developed. This will reduce the time to create an expert system for maintenance from 5 manyears to about 1 manyear for commercial systems. A similar five times reduction in time for military systems might also be possible, but the added overhead and documentation required for military programs may reduce this ratio.

7.1.2 BIT/ATE FINDINGS

The two primary methods of testing military electronics, Built-In Test (BIT) and Automatic Test Equipment (ATE), have reached sophisticated levels of capability but still require excessive manpower for maintenance. A survey was made of current applications of AI in BIT and ATE as well as BIT and ATE problems in order to determine the potential for near term application of artificial intelligence. Information was obtained from published literature and reports, interviews with ATE vendors and relevant R&D groups in government and industry.

The key BIT/ATE findings show a lack of uniform application of design for testability (DFT) techniques:

- o Present application of AI to BIT and ATE is practically nonexistent
- o Designers are not given incentive or feedback on DFT for BIT/ATE
- o There is inadequate management visibility of DFT quality
- o ATE problems are generally due to lack of adequate DFT and BIT

- o ATE test problems are increased because BIT data is often ignored
- o BIT experts are needed since BIT is frequently designed new for each military acquisition.

These findings resulted in the recommendation of applying AI to increase inherent testability by the use of an expert consulting system (Computer Aided Preliminary Design for Testability) that can be used during preliminary design and by use of a Smart BIT chip set.

7.1.3 TESTABILITY APPLICATIONS

Five testability improvement areas were found to have a potential for near term application with, or as part of an AI approach.

- 1) Self improving diagnostics:
 - o Functional test sequences can be cost effectively improved.
 - o Incorporation of diagnostic experience through automated learning is a promising near-term concept.
- 2) More effective fault detection and isolation:
 - o Better Design For Testability is the most cost effective means.
 - o Smart BIT provides the only means to capture fault data in the field.
- 3) Discrimination between false alarms and intermittent faults:
 - This capability will take at least five years to evolve. Information necessary is not yet captured (by Smart BIT) and AI analysis techniques are not yet developed.
- 4) Reduction of skills required for maintenance:
 - AI applied to information processing can reduce specific experience needed by a maintenance technician.
- 5) Integrated Diagnostics:
 - AI can provide cost effective information processing for the system,
 ATE and bench testing.

7.1.4 AI SOLUTIONS TO TESTABILITY PROBLEMS

Technology Breakthroughs

Two major breakthroughs have occurred that will have wide reaching effects on the productivity of maintenance expert system applications and on both developer and user interfaces. These are the development of diagnostic metarules for expert systems and the proliferation of engineering work stations.

Typical useful expert systems presently require more than 5 manyears to develop. In order to create maintenance expert systems quickly, they must be built from generic components so that a large portion of the software can be reused on each implementation. Corporate developments at GE and DEC have created expert systems using these techniques which intelligently manage test sequences and can be adapted to a new system.

Dr. Pau's work at Battelle has developed 400 application independent diagnostic metarules which have already been applied to several experimental systems. These metarules include a circuit network that can describe many types of real electronic faults. This provides a breakthrough both in reducing the costs and increasing the capability of maintenance expert systems.

The engineering work station provides a common host for development of all of the recommended AI applications. Used in conjunction with the rule structure of expert systems, it permits a synergistic development of the requirements common to many of the applications (diagnostic rules, network understanding, graphical display, etc.).

Engineering work stations are gaining widespread acceptance in the aerospace industry. There are multiple sources for both hardware and software that make work stations big enough, fast enough, and cheap enough to be really useful. They will provide direct, personal access to AI applications by the electronics designers. As a result, the majority of the end users will be able to make use of applications in engineering work stations.

AI Applications Evaluated

Nine potential AI applications were developed from the study survey findings and evaluated with respect to testability problem areas. Table 7.1-1 is an applicability

matrix that shows this comparison in chart form. Details supporting these findings follows in summary form:

Computer Aided Preliminary Design for Testability (CAPDT) would be a testability assistant directly available during preliminary design phases.

Smart Built-In Test (Smart BIT) used in boxes or cards can identify intermittent faults and reduce false alarms.

Smart System Integrated Test (Smart SIT) is a system level Smart BIT which performs testing while the system is operating.

Maintenance Expert - Box (ME BOX) provides offline test management with self improvement of functional tests.

Maintenance Expert - System (ME SYS) describes the kind of capability that can be expected during the next three years.

Maintenance Expert—Smart (ME Smart) incorporates the benefits/risks in the 3 to 5 year time period, of including learning capability in the maintenance expert system and its ability to access to Smart BIT information.

Automatic Test Program Generation (ATPG) would be able to understand circuit functional operation; however this application has the lowest figure of merit.

<u>Smart Bench</u> is a maintenance expert system developed for use with bench test equipment controlled by an engineering workstation.

Computer Aided Preliminary Design for Testability (CAPDT)

The findings related to this application are:

CANAL STREET, CONTROL OF STREET,

- Testability experts are needed during initial design to meet new requirements
- o Not enough human testability experts are available
- An AI testability expert can be made

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TESTABILITY FOM X							
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DATA COMPRESSION AND MANAG.	×			×			
INTERFACING & UPWARD COMPAT. X							
MAN/MACHINE INTERFACE X	×	×	×	×		×	

Table 7.1-1 AI Applications to Testability Problems

- o Research is currently underway that supports the concept
- o Large benefits in decreased total LCC as well as decreased production phase cost are possible

MAINTENANCE EXPERT SYSTEMS

A maintenance expert system aids a man in performing functional and diagnostic tests on boxes or systems on-line or off-line. This is the most advanced application of artificial intelligence to testability and is well documented in the literature. Many maintenance systems were examined, including several cost effective generic maintenance expert systems that process off-line test information and saw factory use in 1983.

The five maintenance expert systems (Smart BIT, Smart SIT, ME-Box, ME-System, ME-Smart) evaluated had similar requirements. An evolutionary development is predicted from the proven off-line test management, through on-line observation, to on-line management and incorporation of diagnostics through automated learning (IDEAL). Maintenance expert systems were found to apply best to the system level and box level but not the card level.

The Smart Bench testing concept described in section 5.8 provides a substitute for manual testing by having a computer learn bench functional and diagnostic testing. Testing can then be a man/machine team effort. The Smart Bench can also provide a testbed for techniques common to the other maintenance expert systems.

During the next three years we do not expect any new development in AI that will understand circuit functions and faults through "deep knowledge". It may, however, be possible that AI can be teamed with a system that already understands circuit functions (e.g., a simulation on an engineering workstation). This would be able to simulate circuit faults while a faulty unit is being diagnosed.

SMART BIT

Smart BIT is a design concept capable of identifying intermittent faults, reducing false alarms, and discriminating between the two. It was determined that a programmable, recording BIT integrated circuit chip set is needed as a minimum to achieve testability

improvements. Smart BIT can improve diagnostic techniques of the programmable-recording BIT using a compatable chip set. Signal analysis similar to a technician's approach can also be used by Smart BIT.

7.1.5 AI CAN IMPROVE INFORMATION CAPTURE, FLOW AND PROCESSING

The IDA report Vol. III (45) recognized that poor information flow prevents improvements of testing in the field.

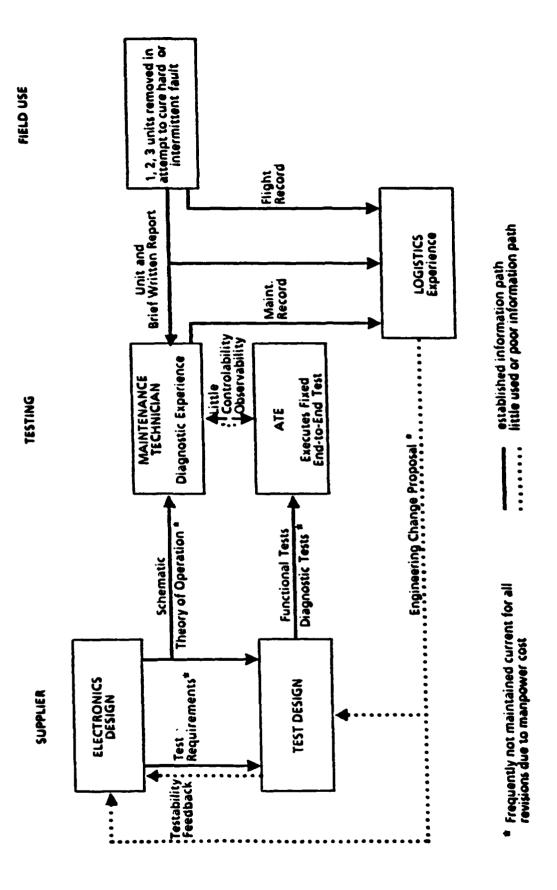
"Diagnostics long term trend analysis could not be supported by information from field data systems.Accuracy and availability of field data in most cases was judged to be insufficient to support requirements, development, short term trend analysis, and timely problem identification."

A majority of the AI applications focus on processing the information associated with testing. The performance of the application is a function of the amount of information available to it. Increasing testability improves the AI application performance, cost-effectiveness, ease of creation, etc.

Figure 7.1-1 presents current testability information flow paths. Current barriers to information flow which have the potential of being reduced by AI applications are:

- o BIT too expensive to redesign to reduce false alarms
- o BIT (and flight records) do not capture environmental information associated with alarms to permit later false alarm analysis
- o Designer is not aware how well he is providing for DFT
- o Operator/maintenance personnel not given feedback on their diagnostic decisions, nor is their diagnostic experience preserved
- o Fixed test sequences on ATE have resulted in long, inflexible testing because test sequence information usually not provided by the test requirements document

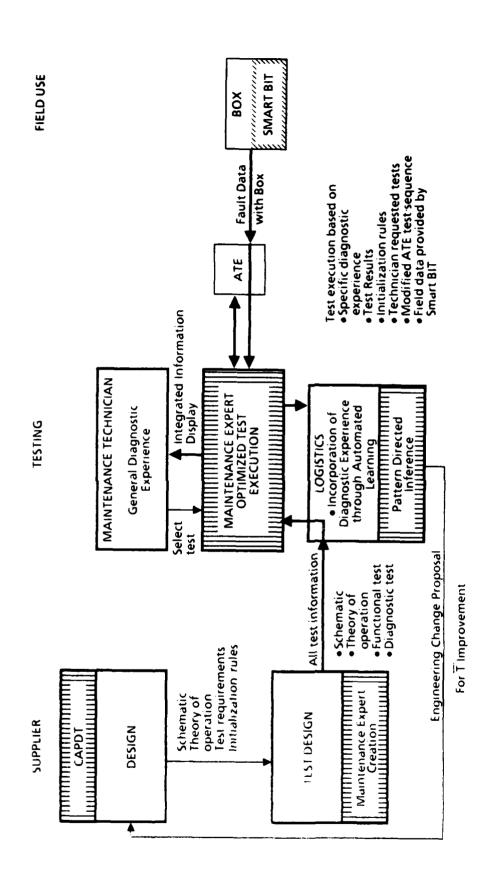
Use of some of the AI applications described in this document have the potential to significantly improve the information flow. This is shown in figure 7.1-2.



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Current Information Flow Is inadequate to Improve Testability Figure 7.1-1



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Figure 7.1-2 Al and Engineering Work Station Improves Information Flow

Engineering work station

7.2 STUDY RECOMMENDATIONS

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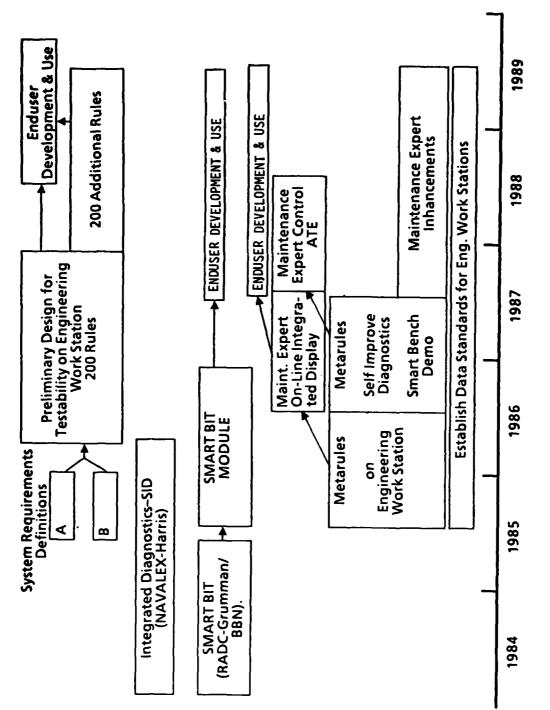
The developments in expert systems and especially diagnostic metarules permits the development of a maintenance expert system template which could be quickly applied to maintenance of many different systems. These same diagnostic metarules could be used for system and box level maintenance experts working in real time, on ATE or on the bench. Diagnostic rules developed by different organizations could be shared if they used standard systems. The limited focus of testability expert systems permits the creation of reusable software.

The engineering work station provides a host which can be used for the development of all of the applications shown in section 7.1 and, in addition, can be the host for use of many of the applications. These work stations are becoming a standardized industry approach and a means to get the resulting AI application tool to the electronics designer as well as a standard for sharing AI techniques and data between different testability research and development organizations.

Operator interface standards (test and graphic) can be developed to reduce retraining and relearning by developers, engineers, and technicians. Data exchange standards are essential for developing a national testability library of design examples and for reusable functional description of some integrated circuits.

Without a cooperative development of the AI opportunities, it will be many years until each aerospace contractor develops cost effective tools to incorporate testability into the designs. Human testability experts do not exist in sufficient quantities to incorporate the desires of the new military testability standards. The AI testability assistant evaluated in this study appears to be the only method available to incorporate all of the necessary test considerations into the early project phases. The military testability standard does not state how testability is to be achieved, instead, it requires audits of testability after each phase of development.

The recommended evolution of development of AI opportunity is shown in figure 7.2-1. The relative cost of each program is proportional to the area, with the metarules being approximately a one million dollar development effort. This shows a possible composite program chart which assumes a synergistic environment, coordinated between developers and end users. Its major features are:



Recommended Evolution of AI Opportunities in Testability Figure 7.2-1

- o Develop diagnostic metarules on engineering work stations
- o Enhance metarules with self improving diagnostic capability
- o Provide resulting maintenance expert as a tool
- o Develop recording-reprogrammable BIT chip set to gather critical fault information
- o Later, enhance the chip set with Smart BIT capabilities, and provide it as tool which can be used by contractors
- o Develop Computer Aided Preliminary Design For Testability which is crucial to early testability insertion
- o Develop a national library of testability examples and rules which can be used on the engineering work station

By coordinating the use of the same components in the development, substantial time and cost is saved:

- o Same data interchange format for rule and data sharing
- o Same AI language
- o Same Rule format for Diagnostics-Metarules are System Independent
 - . Has potential for low cost AI application development for each system
- o Shared AI technique development
- o Same operator interface for all applications
 - . Reduces learning time for engineers and technicians
 - . Integrated information display
- o Same System and Circuit description as that used by designers on their engineering work stations

All opportunities permit the acceleration of testability insertion by the aerospace contractors by providing them with useful tools years before they would otherwise be developed. The current amount of LCC devoted to testing is 25%. When the new testability standards are imposed this might be expected to increase a few percentage points into the early 90's while the contractors each develop Smart BIT, testability assistants, maintenance experts, etc. Then it is predicted that the costs associated with testability would drop by at least 5%, to less than 25%.

The cost of this study's recommended development program (figure 7.2-1) is approximately \$10M. The cost of avionics each year is \$10B. The acceleration of testability insertion could result in an avionics cost savings of at least 2% per year (\$200M) over the

independent development of testability tools. Over a 5 year period this amounts to a \$1B cost savings for \$10M investment.

Recommendations to Industry

There are many paths to incorporating AI in a product. The longest path is to ask an engineer to use the AI language on an existing general purpose computer to make an expert system. This approach will take many, many man years to get beyond the trivial (50 rule) stage. There are an assortment of commercially available systems for producing expert systems which eliminate reinvention of the wheel.

While it is currently costly to develop the rules of an expert system by extracting them from experts, soon developments similar to the Boeing Computer Services Expertise Transfer System will reduce the need for knowledge engineers in creating an expert system.

For development of maintenance expert systems, participation with Dr. Pau is recommended. The participation cost for each sponsor is in the range of \$10,000 to \$20,000 for nine months. (Battelle, Geneva Research Centres; 7, route de Grieze; 1227 Carouge; Geneva, Switzerland or Dr. Barry Brunstein., Battelle - Digital Systems and Technology Section, 505 King Ave, Columbus, Ohio, 43201).

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Page	Subject
136	THEOREM PROVING
137	NATURAL LANGUAGE, VOICE, SPEECH
138	DATA BASE RETRIEVAL/REPRESENTATION
138	EXPERT SYSTEMS
140	MAINTENANCE EXPERT
143	ROBOTICS
144	AUTOMATIC PROGRAMMING
144	VISION
144	PATTERN RECOGNITION
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147	MAINTENANCE TRAINING
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- 2) M, FI, BIT, and redundancy are key factors influencing A.
- 3) Good front-end engineering is the most effective key step toward improving RAM.
- 4) Many RAM problems cannot be anticipated and will show up during FSD testing, during transition to production, during production, and after field introduction.

The only way to reach achievable levels of R is by an iterative method of testing, identifying etc.

5) Panel could not quantify the cost and benefits of achieving increased RAM. The formal R program costs 4-6% of the RDT&E costs and additional costs of maybe 10-20% of the RDT&E costs if iterative redesign and test are required during development and transistion to production(wag).

R&M Study of IDA Vol III, August 1983, Institute of Defense Analysis, HIGH PAY-OFF AREAS Vol III part 7.0

"CAD can truly make R&M part of mainstream design engineering." (pg 4)

"A maturation program for BIT has also proven to be essential" (pg 5)

SIGNIFICANT FINDINGS/OBSERVATIONS part 8.0

"In 7 of the 8 cases studied, financial incentives were judged to have been a significant factor in focusing management's attention on R&M" (pg 1.)

"It seems though that R&M emphasis may have been lacking during the concept and even in development and validation where the potential of a system is really established" (pg 2.)

"Accuracy and availability of field data in most cases was judged to be insufficient to support requirements development, short term trend analysis, and timely problem identification" (pg 4.)

"A reliability growth program should use data from all test and operational sources. The program should be structured at the beginning to treat every failure or operating anomaly as a potential reliability growth opportunity" (pg 5.0-26)

"..strong consideration should be given to extending planned BIT maturation into the operational phase." (pg 5.0-29)

Randall Davis, Howard Shrobe, Representing Structure and Behavior of Digital Hardware, 75-82, Computer, Oct. 1983, MIT AI LAB.

Harold S. Balaban, William R. Simpson, Testability/Fault Isolation by Adaptive Strategy, Proceedings Reliability and Maintainability Symposium 1983, 344-349, ARINC Develops nodal connection interaction analysis on an Apple computer. Program is called STAMP.

W. R. Simpson, J. R. Agre, Adaptive Fault Isolation with Learning, IEEE AUTOTESTCON, 1983, 331-335, ARINC

Directly incorporates field information of test time and failure frequency to optimize the testing sequence. Does not currently provide for additional test strategies to be recorded or suggested by the test operator. Tests can be optimized for cost (peace) or time (war) by the operator at test time. Explanations can be requested from the system, such as video images of how to perform the test (currently on videotape). Presently all test strategies are based on all tests at a particular location. This could be changed to a weighted moving average at a location or be based on information from more than one site.

Shunichi Toida, A Graph Model for Fault Diagnosis, <u>Journal of Digital Systems</u>, VI, #4. 1982, 345-365,

Methods to determine the smallest number of test points needed, with such constraints as mimimizing the total number of tests.

L. F. Pau, Failures Detection Processes by Pattern Recognition and Expert Systems, submitted for publication by <u>Pattern Recognition Letters</u>. Includes meta-rules for electronic diagnosis, the most advanced in world.

- L. F. Pau, J. Rasmusson, Application of Pattern Recognition to Failure Analysis and Diagnosis, 429-446, Human Detection and Diagnosis of System Failures, 1981
- L. F. Pau, An Adaptive Signal Classification Procedure Application to Aircraft Engine Monitoring, Pattern Recognition, Vol 9, 1977, 121-130
- L. F. Pau, Failure Diagnosis and Performance Monitoring, Marcel Dekker NY \$49 1981, 427, Battelle Switzerland,

This is the only book which clearly addresses the theoretical and practical aspects of sophisticated techniques for failure analysis. He discusses the concepts of which we call self-improving diagnostics (learning), Smart Built-In-Test (observability) without referring to AI once(pattern recognition). Some of the chapter titles are: Degradation Processes (for mechanical systems), Test sequencing with a priori information for failure locatization, R&M data banks, Failure and Maintenance data analysis, Correspondence Analysis for Failure analysis, Automated Failure diagnosis by Pattern recognition, adaptive failure diagnosis and performance monitoring.

Michael L. Arington, The 'Experience Algorithm' in Automating Isolation of Single and Multiple Faults, ATE Central Proceedings, October 1983, Magnavox Ft. Wayne Indiana Describes some concepts for what others call self improving diagnostics. Decision program would choose the most likely failures based on the highest number of previous failures. System would also compare fault signatures. "Experience programs are not meant to replace or even reduce fault isolation algorithms or the need for testability but they can enhance and complement them technically and economically." "Some cases will require as little as tabulation tables of correct and incorrect diagnosis. Other applications may require the sophistication of AI".

LES: A Model-Based Expert System for Electronic Maintenance, T.J. Laffey, W. A. Perkins, O. Firschein, Fall 1983, Lockheed Palo Alto Research Lab

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The Lockheed Expert System (LES) uses expert knowledge in the form of IF-THEN rules and knowledge of the structure, function, and causal relations of the device under test. It graphically displays the interrelationships of the device being tested. This aids in the technician's diagnosis process. It has been applied to a large electronic system of 16 equipment cabinets which included built-in-test. Future systems should integrate the BITE with LES, so as to eliminate much of the human interaction. They are currently adding voice input/output to free themselves from the terminal console (like TI PEAM). They also want the system to adapt to the skill of the user, but are not yet concerned with self-improving diagnosis.

George C. Sumner, Knowledge-Based Systems Maintenance Applications, <u>IEEE 1982</u> AUTOTESTCON, Dayton, Ohio, 472-473

Knowledge based systems promise improvement in failure diagnosis and can-not-duplicate conditions of electronics maintenance.

D. R. Antonelli, The Application of Artificial Intelligence To A Maintenance and Diagnostic Information System (MDIS), 1983, Proceedings of the Joint Services Workshop On Artificial Intelligence and Maintenance, Boulder, Co. To be published

Artificial Intelligence to Support Avionics Maintenance Diagnostics A State-of-the-Art-Assessment, Dr. Curt Blais, Dr. Benjamin Schwartz, Mr. Richard Schwarz. Dr. Stephen Tolchin, Dr. Chelsea White, System Exploration Inc., Jan 1984, for AF Human Resources lab, Wright Patterson. No publication number.

Causal and Teleological Reasoning in Circuit Recognition, Johan deKleer, Sept 1979, 1-208

This thesis presents a theory of human-like reasoning in the general domain of designed physical systems, and in particular, electronic circuits. One aspect of the theory, causal analysis, describes how the behavior of individual components can be combined to explain the behavior of composite systems. Another aspect of the theory, teleological analysis, describes how the notion that the system has a purpose can be used to aid this causal analysis.

J. W. Lewis, PhD, F. S. Lynch, ScD, GETREE: A Knowledge Management Tool, 1983, IEEE, CHI

General Electric Company, Corporate Research and Development. In practical expert systems, regardless of inference technology, the accuracy and completeness of the knowledge base determine expert system performance, and the cost of acquiring that knowledge base tends to dominate all other hardware and software costs. To reduce knowledge acquisition cost and error rate, GETREE--a new interactive knowledge management system--is being designed and implemented in GE Corporate Research. In the new system, the knowledge base is represented as an (almost tree-like) network of nodes which can be displayed and manipulated on a personal computer workstation. Users--even unsophisticated users--can build and navigate these networks, modify nodes and connecting arcs, verify correctness visually, follow the execution of inference engines, and generate equivalent code to be run in more constrained target environments. Consequently, with GETREE the user-organization can have full responsibility for and control of the knowledge base.

R	ROBOTICS	
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Irene C. Peden, Artificial Intelligence and Robotics, Army Science Board, Sept. 1982

H. McIlvaine Parsons, Greg P. Kearsley, Robotics and Human Factors: Current Status and Future Prospects, Human Factors, 24, 5, 1982, 535-552

The most important question is the division of labor between robots and humans. Humans participate in robot systems in 9 activites: surveillance, intervention, maintenance, hardware and software design of interfaces with operators, procedure development, accident prevention, and training.

A Computer Vision and Robotics Laboratory, R. A. Jarvis, <u>IEEE Computer</u>, June 1982, 9-23

Color vision is combined with a robot arm and ultra-sonic ranging in this off-the-shelf system. Color and range aids in scene segmentation with additional feedback via the robot arm.

M. Brady, J M. Hollerbach, T. L. Johnson, T. Lozano-Perez, M Mason, Robot Motion: Planning and Control, McGraw Hill \$37.50, MIT AI Lab

AP AUTOMATIC PROGRAMMING	
Francesco Caio, Giovanni Guida, Marco Somalvico, Problem Solving As A Basis for Program Synthesis: Design and Experimentation of the BIS System, Int. Jrnl. Man-Machine Studies, 1982, pg 173-188, automatic programming synthesis, DRA The paper is devoted to assessing and motivating the central role that classical problem solving techniques can play in the development of a program synthesis system. Uses bidirectional synthesis, which considers the task of automatic programming as based on the cooperation between: 1) a top-down activity of problem reduction 2) a bottom-up activity of binding together of program modules in a structured way	
Moreover, this approach is experimentally supported by the development of the BIS (Bidirectional Synthesizer) system for interactive synthesis of LISP Programs. BIS is developed on a UNIVAC 1100/80 and is written in LISP.	
Richard C. Waters, A Method for Automatically Analyzing Programs, 6th IJCAI, 20-23 August 1979, pg 935-941. This paper presents a method for automatically analyzing programs and discusses why it is a useful way to look at programs. The method is based on the idea that there are only a few basic ways in which the logical structure of programs is built up. An experiment is presented which shows that this accounts for the structure of a large class of programs. The paper discusses how the method can be used to automatically analyze the structure of a program, and how the resulting analysis can be used to guide a proof of correctness for the program. An automatic system is described which performs this type of analysis.	
VI VISION	
W. A. Perkins, Model-Based Component Board Inspection, 1982, IEEE 6th International Conf. on Pattern Recognition Gray-scale computer vision for inspection of a flat surface: looking for correct component, correct orientation and position, and other features. D.H. Ballard, C.M. Brown, Computer Vision, 1982, 523, Prentice-Hall, Strong AI flavor to the book,	
George Koutures "Automated Optical Inspection Paces Future PC Production", Electronic Packaging and Production pg. 126-128, June 1983	
P PATTERN RECOGNITION	
Yoh-Han Pao, George W. Ernst, Context-Directed Pattern Recognition and Machine Intelligence Techniques for Information Processing: a Tutorial, IEEE EH0193-3, 1982, 577+,	
This is a collection of papers, primarily during last 5 years	
R Nevatia, Machine Perception, 1982, Prentice Hall, 209 pages.	

Charles L. Forgy RETE: A Fast Algorithm for the Many Pattern/Many Object Pattern Match Problem, Artificial Intelligence, September 1982, 17-37

By compiling objects and patterns into single word descriptions, RETE is able to very quickly perform searches for many objects with many patterns in a single scan.

Douglas S. Tudhope, John V. Oldfield, A High-Level Recognizer for Schematic Diagrams, IEEE Transactions on Computer Graphics and Applications, May/June 1983, 33-40, Uses AI to store circuit diagram information in a global, modifiable database.

CAD		AIRPA PECIAL
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G.J Sussman, Computer Aided Evolutionary Design for Digital Integrated Systems, MIT AIM 526, May 1979, AD-A078124

Mark J Stefik, Johan de Kleer, Prospects for Expert Systems in CAD, Xerox Palo Alto Research Center, Computer Design, April 21 1983, 65-76, PALLADIO is an expert system developed by Xerox and Stanford for circuit design. It uses Linked Module Abstraction (LMA), CRL and CPS.

M. W. Krueger, R. E. Cullingford, D. A. Bellavance, Control Issues in a Multiprocess Computer-Aided Design System Containing Expert Knowledge, IEEE 1981 Cybernetics and Society, 139-143

CADHELP is a knowledge-based CAD system for the design of digital logic circuits. This system contains a knowledge representation describing each of the graphic features that the system provides. These feature scripts can be used to generate graphic demonstration and text explanations of the use of these features.

The use of scripts to document the system has been extended to include control scripts. These describe the interaction of system experts responsible for staging graphic modules and assimilation of their results into a Design Knowledge Structure. Also of interest is the fact that the control scripts are used to control the events they describe. Thus, there is no possible conflict between execution and documentation.

Tan E. Kelly, Louis L. Steinberg, Rutgers University, The Critter System: Analyzing Digital Circuits by Propagating Behaviors and Specifications AAAI-82, 284-289, Reasons about digital HW designs but needs to be extended to practical circuits which include feedback and components with state.

Tom M Mitchell, Louis I Steinberg etc, An Intelligent Aid for Circuit Redesign, AAAI 1983, Rutgers University

Knowledge based circuit redesign has causal reasoning about circuits and purpose of the circuit. This redirection of their CRITTER work has a narrow scope, and appears to have some near-term uses. This has some applicability to the testability assistant which must also compare effects of changes to a circuit.

Harold Brown, Christopher Tong, Gordon Foyster, Palladio: An Exploratory Environment for Circuit Design, Computer, December 1983, Stanford VLSI prototype AI circuit designer.

Thomas L. Fennell, Thomas A. Nicolino, Computer Aided Testability, 1984 Proceedings Annual Reliability and Maintainability Symp., RADC contract to Boeing, Condensed information of RADC TR-83-257, outlined in section 8.4.4 of this report.

T. J. Kowalski, D.E. Thomas, The VLSI Design Automation Assistant:Learning to Walk IEEE International Symposium On Circuits and Systems, May 1983, 186-189, Carnegie-Mellon University

A Design Automation Assistant using AI techniques was used to design different versions of the 6502 microprocessor. Use of OPS-5 started with 70 rules and grew to 130 rules. Future Design Automation Assistants are planned to include design of a VAX computer.

C.J. Rimkus, M. R. Wayne, D. D. Cheng, F. J. Magistro, Structured Design Verification: Function and Timing, 20th Design Automation Conference, 1983, 246-251, IBM-Poughkeepsie

VLSI needs to be 100% error free the first time. Table gives change cost factors at various points in the design cycle. A change in engineering objectives has a cost factor =1. A change at detailed logic mode has a cost of 20, but product rework has cost factor of possibly 10,000.

Max Schindler, Computer-Aided Engineering Comes of Age, Electronic Design, Nov. 11, 1982, 97-104

Most are based on 68000. With CAE, the designer creates a circuit (or machine) in computer-readable form from the very beginning. The same data base can then provide the inputs either for a placement or routing or for a simulation routine; if the results lead to design changes, the inputs are automatically integrated into the data base. CAE is done on a workstation, CAD can be done in batch.

A. L. Elias, Computer-Aided Engineering: The AI Connection, <u>Astronautics and Aeronautics</u>, July/August 1983, 48-54, MIT

Martin F. Rooney, Stephen E. Smith, Artificial Intelligence in Engineering Design, Computers and Structures, 1983, 16, 279-288

Richard E. Cullingford, Myron W. Kreuger, Mallory Selfridge, Marie A. Bienkowski, Automated Explanations as a Component of a Computer-Aided Design System, IEEE Transactions on Systems, Man, and Cybernetics, March/April 1982, SMC-12, 2, 168-181, Univ of Connecticut, Rensselaer Polytechnic Describes CADHELP

T. J. Kowalski, D.E. Thomas, The VLSI Design Automation Assistant: First Steps, IEEE CH 1856, 1983, 126-129

Henry L. Nattrass, Glen K. Okita, Some Computer Aided Engineering System Design Principles, 20th Design Automation Conference, 1983, 571-577, Hewlett Packard Describes CAE at HP, including Hierarchical design file, database, etc similar to commercial engineering work stations.

Gil Bassal, Designing Computers - Special Report Electronic Design, April 19, 1984, 91-104

Good overview of engineering workstation projects of ten companies. Includes ATPG and other simulation packages. LISP Machines' Newdraw logic design program includes some AI features

Thomas H. Bruggere, Elizabeth Holloman, "Tools for Computer-Aided Engineering", IEEE Computer Graphics and Applications, Dec 1983, pg 48-53. Explains electronic design tools and other tools for the Mentor Graphics engineering work station.

P.B. Stevens, Workstations and Special Purpose Hardware, Database Engineering, March Stephen Evanchzuk, Special Report: Work Stations, Integrating the Engineers Environment, Electronics, May 1984, pg 121-130. Includes price trends. Mentor has 24% market share, Daisy 32%. ---MT------ MAINTENANCE TRAINING ------Ruston M. Hunt, Richard L. Henneman, William B. Rouse, Characterizing the Development of Human Expertise in Simulated Fault Diagnosis Tasks IEEE 1981 Cybernetics and Society, 369-374, Discusses a wide range of human problem solving characteristics useful in predicting and evaluating performance on simulated fault diagnosis tasks. Performance metrics considered include project measures such as error frequency and information gain per action. These measures are used to explain the varying levels of expertise exhibited by subjects on the simulated tasks. P. E. Van Hemel, W. J. King, Simulation Techniques In Operator And Maintenance Training, Performance Assessment, And Personnel Selection, Computer and Indus. Engng.. 5, 2, 105-112, Examines the use of synthetic simulators for training personnel who operate and maintain electronic and other systems. It uses past problems as a basis for simulation. Has examples of Army, Navy and Air Force programs. D Sleeman, J. S. Brown, Intelligent Tutoring Systems, Academic Press, 1982 Francis D. Fisher, Computer-Assisted Education: What's Not Happening, Journal of Computer-Based Instruction, Summer 1982, 9 #1, Dr. Janathin Miller, Chairperson, The Status of Training Technology in the ATE Community, IEEE 1982 AUTOTESTCON, 12-14 October 1982, 110-113 Outlines future changes in ATE technical training programs due to advances in instructional media including: interactive video, videodisc, CAD/CAM, computer assisted/managed instruction, distributed information systems, robotics, etc. ----- MACHINE LEARNING -----Ryszard S. Michalski, Jaime G. Carbonell, Tom M. Mitchell, Machine Learning: An Artificial Intelligence Approach, Tioga Publishing Co., 1983, 572, Very comprehensive coverage. This book appears to be a first for this field. Learning from Examples Inductive Learning SUBJECTS: In Problem-Solving and Planning By Analogy By Experiment Learning from Observation and Discovery AM EURISKO BACON Conceptual Clustering Learning from Instruction Advice transformation into Search Proc. Learning by Being Told KLAUS NONOKLAUS Applied Learning Systems Chess CAI Also has a bibliography of 572 items

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Jack Mostow, Machine Learning Workshop, SIGART Newsletter, October 1983, 24-31 Provides a summary and comments on the papers and talks presented at the 1983 Machine Learning Workshop.

Proceedings of the International Machine Learning Workshop, Dept. of Computer Science, U. of Illinois, Urbana, June 22-24 1983, 234,

R.S. Michalski, R.L. Chilausky, Knowledge Acquisition By Encoding Expert Rules Versus Computer Induction From Examples, Int. Jrnl. Man-Machine Studies, 16, 1980, 63-87, Current methods of knowledge acquisition rely entirely on the direct representation of knowledge of experts, which usually is a very time- and effort-consuming task. The paper presents results from an experiment to compare the above method of knowledge acquisition with a method based on inductive learning from examples. The comparison was done in the context of developing rules for soybean disease diagnosis and has demonstrated an advantage of the inductively derived rules in performing a testing task (which involved diagnosing a few hundred cases of soybean diseases).

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R. S. Michalski, R. L. Chilausky, Learning by Being Told and Learning from Examples: An Experimental Comparison of the Two Methods of Knowledge Acquisition in the Context of Developing an Expert System for Soybean Desease Diagnosis, int. j. policy Anal. and Inf. Systems, 4, 2, 125-161, June 1980

This paper contrasts the method of knowledge acquisition by encoding decision rules of human experts with that of learning the rules (by means of an inductive program) from examples of decisions made by these experts.

Ryszard S. Michalski, Robert E. Stepp, Automated Construction of Classification: Conceptual Clustering Versus Numerical Taxonomy, IEEE Transactions on Pattern Analysis and Machine Intelligence, July 1983, 396-410, Univ. of Ill.

His CLUSTER/2 program is compared to 18 numerical taxonomy methods for two example cases.

Dana Nau, James Reggia, Pearl Wang, Knowledge-based Problem Solving without Production Rules, <u>Trends and Applications</u>: Automating Intelligent Behavior, May 1983, IEEE Cat 83CH1887-9.

Generalization of set covering problem which captures several intuitively plausible features of human diagnostic interference and directly address problem of multiple simultaneous disorders. KMS.HT is a Knowledge Management diagnostic subsystem which can "hypothesize and test".

John E. Gaffney, Jr., I. Randy Racer, A Learning Interpretive Decision Algorithm For Severe Storm Forecasting Support, Trends and Applications: Automating Intelligent Behavior, Applications and Frontiers, Proceedings, May 1983, IEEE Cat 83CH1887-9.

National Weather Service Silver Spring Maryland. Al decision aide learns by observing only 13 key fuzzy parameters. Each of the attributes are linguistically described by "weak, moderate, strong" etc and the outcome is a probability of a severe storm rated from .15 to 95. This is similar to discriminate analysis except that coefficients are heuristically derived from developers experience. The nonlinear forecast functions uses technique from preference theory. He stresses that this AIDS the forecaster in doing HIS job.

Casimir A. Kulikowski, Knowledge Acquisition and Learning in EXPERT, <u>Proceedings of the International Machine Learning Workshop</u>, Dept. of Computer Science, U. of Illinois, Urbana, June 22-24 1983.

SEEK provides a data base of problem solving examples which permits: induce reasoning rules using partial knowledge of casual and hierarchial relationships, suggest improvements to human rules.

Alan Bundy, Bernard Silver, A Critical Survey of Rule Learning Programs, European Conf. on AI, July 1982, pg 151-157.

Comparison of ELM and AMBER of Langley, LEX of Mitchell, Model Inference of Shapiro, and Youngs extensions of Winston (75). Authors find that similar methods are used to tackle similar problems, with every program having a critic for identifying faults and a modifier for correcting faults.

Jaime G. Carbonell, Ryszard S. Michalski, Tom M. Mitchell, Machine Learning: A Historical and Methodological Analysis, AI Magazine, Fall 1983.

Good summary of taxonomy of machine learning. Describes types of learning and the 10 types of knowledge classification descriptions.

James A. Reggia, Pearl Y. Wang, Dana S. Nau, Minimal Set Covers As a Model for Diagnostic Problem Solving, MEDCOMP, 1982, pg 340-347, HL.

This model offers a framework for multiple simultaneous disorders for a framework for a theory of diagnostic inference. This is similar to Michalski's methodology of inductive learning.

P. R. Innocent, Towards Self-Adaptive Interface Systems, Int. Jrnl. Man-Machine Studies, Academic Press Inc., 16, 1982, 287-299,

This paper follows a trend towards more user-oriented design approaches to interactive computer systems. The implicit goal in this trend is the development of more "natural" systems. The term "soft facade" is used to describe a modifiable interface to a system.

Patrick H. Winston, Learning New Principles From Precedents and Exercises, <u>Artificial</u> Intelligence, 19, 3, 1982, 321-350.

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Elaine Rich, Artificial Intelligence, McGraw Hill \$27., 436, May 1983, Univ. Texas at Austin

Reader is a programmer, computer scientist or graduate student. This is the only recent book to provide a balanced treatment of a majority of the AI fields.

Edward A Feigenbaum, Pamela McCorduck, The Fifth Generation - Artificial Intelligence and Japan's Computer Challenge to the World, March 1983, 275, Addison Wesley \$15.55, Feigenbaum is a Stanford expert in AI writing a popular book. Japan's fifth generation project is described very well, although critically, in 50 pages. Coverage of meager attempts by England and France to counter Japan takes up 20 pages.

Trends and Applications: Automating Intelligent Behavior, Applications and Frontiers, Proceedings, May 1983, IEEE Cat 83CH1887-9, NBS Excellent overview symposium

*European Conference AI, 1982, 300 aprox, Yves Kodratoff, ECAI-82 Conf, LRI Batimant 490, F91405, Orsay CEDEX, France \$20

Robert M. Glorioso, C. Colon Osorio, Engineering Intelligent Systems: Concepts, Theory, and Applications, Digital Press, 1980, 472,

A comprehensive overview showing how current concepts and techniques in various fields including electrical engineering, mathematics, and neuro-physiology, contribute to designing intelligent systems.

Nils J. Nilsson, Principles of Artificial Intelligence, Tioga Publishing, 1980, 476. Describes fundamental artificial intelligence (AI) ideas that underlie many of its applications. The important roles played in AI by generalized production systems and the predicate calculus are stressed. The text is designed for a senior or first-year graduate course in AI.

Publications Bibliography MIT AI LAB, March 1983, MIT AI LAB, Cambridge, MA 02139, 617-253-6218, AI Memo # 191,

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AI TESTING

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Artificial Intelligence AI Magazine quarterly

ACM SIGART Special Interest Group in AI quarterly magazine with excellent review of current AI work and publications.

Journal of Cybernetics now Cybernetics and Systems
Journal of Cybernetics and Information Sciences
International Journal of Man/Machine Studies
Systems, Man, and Cybernetics Review
Cybernetics and Systems
Computer and Information Systems Abstracts
Machine Mediated Learning, An International J. Voll #1 Spring 1983
Electronic Test
ATE Newsletter NAVY quarterly ELEX 08TA Naval Electronic Sys. Command, Wash DC
20363, covers testability, ATLAS, Integrated Diagnostics, Military research groups

CONFERENCES (ANNUAL)

AUTOTESTCON IEEE

International Test and Measurement Conference
Computer-Aided Design IEEE International Conference
CAD-CON Computer Aided Design Conf. sponsored by magazine
Total System Reliability Symposium IEEE
Reliablity and Maintainablity Symposium (DEC. 1983)
International Symposium on Fault Tolerant Computing
National Aerospace and Electronics Conference
Computers in Aerospace Conference IEEE/ AIAA
Digital Avionics Conf biannual 4th 1981 IEEE AIAA
Advanced Automation, International Conference IEEE

Computer Applications in Medical Care Annual Symposium IEEE International Conf on Pattern Recognition
Proceeding Pattern Recognition and Image Processing
Now Computer Vision and Pattern Recog.
International Joint AI (BIANNUAL) (...79 81 83)
International Conference on Cybernetics 10th = 1983

International Conf on System Sciences, Hawaii Cybernetics and Society, International Conf. CIC Q300 II7
AIM AI MISC
Special Issue on Knowledge Engineering, Computer, 1983.
A. Bolour et al, The Role of Time in Information Processing, SIGART, April 1982, 28-48, Annotated bibliography of 69 papers that deal with temporal aspects of AI and information processing. Instead of a snapshot description this allows real world models which include history and evolution. #32 The Notion of Time in Medical Records Methods of Information in Med 4/78 #51 An Interval-based representation of Temporal Knowledge IJAI August 81 #63 TERM: An approach to include the time dimension in the entity-relationship model Second Int. Conf. on the Entity Relationship Oct 1981
James F. Allen, Maintaining Knowledge about Temporal Intervals, Communications of the ACM, November 1983, 832-843, Univ. of Rochester Interval-based temporal logic is developed and examples are given for the following database types: historical data, modeling processes and process interaction, and interactive system where present moment is continually updated.
The Current State of Al: One Man's Opinion, Roger C. Schank, Yale University, Al Magazine, Winter/Spring 1983, 3-8,
David Waltz Chairman, Artificial Intelligence: An Assessment of the State-of-the-Art and Recommendation for Future Directions, AI Magazine, Fall 1983, In depth analysis of natural language and expert systems with recommendations for next 5-10 years.
A. A. Araya, Learning Modalities in Artificial Intelligence Systems: A Framework and Review, Proceedings of the 2nd International Conference on Computer Science, August 1982, 54-84 Intelligent systems should possess two fundamental capabilities: problem solving and learning. Problem solving capabilities allow an intelligent system to cope with problems in a given domain. Learning capabilities make it possible for an intelligent system to improve the solution to problems within its current reach, or to cope with new problems. This paper examines research in Artificial Intelligence from the perspective of 'learning' with the purpose of: 1) developing and understanding of the problem of learning from the AI point of view, and 2) characterizing the current state of the art on learning in AI. (35 refs.)
R. B. Banerji, Theory of Problem Solving: A Branch of Artificial Intelligence, Proc. IEEE. December 1982, 1428-1448, GPS
R. B. Banerji, Theory of Problem Solving: A Branch of Artificial Intelligence, Proc. IEEE. December 1982, 1428-1448, GPS Judea Pearl, Antonio Leal, Joseph Saleh. GODDESS: A Goal-Directed Decision Structuring System. IEEE Transactions on Pattern Analysis and Machine Intelligence. PAMI-4, 3, May 1982, 250-262 D. G. Shapiro, Sniffer: A System that Understands Bugs June 1981, AD-A102158, MIT AIM 638.
D. G. Shapiro, Sniffer: A System that Understands Bugs June 1981, AD-A102158, MIT AIM 638,
This Masters thesis develops expert system for software program debugging by having an assortment of experts which can be applied to suspect code. This might also be useful

- for V/V of test program software to see that all of the constraints have been met: accuracy, timing, error callout, comments etc.
- D. A. McAllester, Reasoning Utility Package User's Manual, April 1982, AD-A114756, MIT AIM 667.

Contains a Truth Maintenance Package (TMS) which allows separation of assumptions from solid facts and keeps track of the effect of changes to an expert system.

- B. Chandrasekaran, Toward a Taxonomy of Problem Solving Types, AI Magazine, 9-17, Winter/Spring 1983,
- M. S. Y. Wang, Keh-Chiang Yu, A Hierarchical View of Decision Support System Software, Proceeding of 16th conf on System Sciences 1983, 482-489, Univ of Texas/Austin

Youji Fukada, Primary Algorithm for the Understanding of Logic Circuit Diagrams, Pattern Recognition Conf 1982 IEEE, 706-709, Mitsubishi Japan. Inputs schematic diagrams into computer from drawings.

G. Neugebauer, DOCUMENT ANALYSIS The TEXT SCANNER: A Model for Analyzing and Classifying Document Elements, Pattern Recognition Conf 1982 IEEE, 486-488, Siemens, Pattern Recognition

John W. Verity, LISP Markets Grow, <u>Datamation</u>, Oct 1983, 92-100
While Symbolics, Xerox and LISP Machine Inc. control the \$50 Million market for personal LISP machines, a dozen or so startups in the artificial intelligence field are fueling interest in new LISP tools. Names many new small AI companies.

Randall Davis, Interactive Transfer of Expertise: Acquisition of New Inference Rules, Artificial Intelligence, 12, 1979, 1210157

TEIRESIAS is a program designed to provide assistance on the task of building knowledge-based systems. It facilitates the interactive transfer of knowledge from a human expert to the system, in a high level dialog conducted in a restricted subset of natural language. The concept of meta-level knowledge is described and illustrations are given of its utility in knowledge acquisition and its contribution to the more general issues of creating an intelligent program.

James B. Schultz, Weapons That Think, Defense Electronics, January 1983, 74-80 Pentagon analysts look to AI to solve problems in: 1) C3I Fusion (information reduction), 2) Missile Guidance, 3) Robotic Tanks, 4) Intelligence (translate language, read in interpretations based on dialects, local phraseology, and inflections) 5) Electronic Warfare.

Michael Georgeff, Strategic Search, <u>Australia Computer Science Communications</u>, 2, 1, Jan 1980, 25-38

Strategic search out performs heuristic searching.

- 曹重のなどのののの重要のないののであり、大きななななないとしていたなどのである。

Edward C. Taylor, Artificial Intelligence in the Air-Land Battle. Astronautics & Aeronautics, July/August 1983, 55-59, AIAA, TRW Defense Systems Group The key limit in a real time intelligence system is not the volume of data the analysts can get to, but rather the mental limits of the analysts. This paper briefly reviews several knowledge engineering and AI systems, noting the similarities between capabilities of existing systems and the needs of military situation assessment. The author concludes that development of an operational military expert system is a tough challenge, but is technologically and culturally feasible.

A J. Kunert, ATE Applications of Artificial Intelligence, 1982 IEEE AUTOTESTCON, 84-87, Naval Air Eng. Center,

The author does not see near term uses of AI for ATE due to memory and speed limitations. The Navy would like friendlier ATE that would have a dialogue with an operator while testing. An Expert Diagnostician would have knowledge of previous faults and causes which it could apply to future diagnosis. Self improving diagnostics are alluded to in addition to BIT and monitor IC, as well as CAD systems which include a testability review which are aware of the capabilities of the target ATE.

Institute for Defense Analysis, Built-In-Test Requirements Workshop IDA 1981 P-1600 219 Landmark paper, widely referred to.

Betty Sponaugle, ATE NEWSLETTER, ELEX 08TA Naval Electronic Systems Command DC 20363.

Quarterly newsletter of Automatic Test Equipment news in DoD. Covers testability, ATLAS, MATE, VHSIC Self-test, Army Diagnostic Technology.

- D. E. Tuttle, R. Loveless, Built-In-Test and External Tester Reliability Characteristics, March 1980, AD-A083-488, RADC TR-80-32, Lockheed
- J. G. Malcolm, BIT False Alarms: An Important Factor in Operational Readiness, Proceed. Reliability and Maintainability Symposium, IEEE, 1982, 206-212, Hughes, Excellent paper on BIT false alarms, including AI solution ideas.
- Robert T. Chien, Roderick J. Fletcher, William P. C. Ho, Larry J. Peterson, On the Use of Procedural Models for Generation of Test Programs, IEEE Transactions on Circuits and Systems, July 1979, IEEE, CAS-26, 7, 555-557.

An approach based on artificial intelligence concepts is developed for automatic generation of test programs for analog circuits. The programs will, with the help of automatic test equipment (ATE), make appropriate measurements and deduce the location of potential faults in analog circuit boards.

J. G. Malcolm, Practical Application of Bayes' Formula, Reliability and Maintainability Annual Proceedings, 1983, 180-186, Hughes

The author 'proves' that false alarms cannot be eliminated for the single measurement case.

J. G. Malcolm, G. L. Foreman, The Need: Improved Diagnostics—Rather than Improved Reliability, Proceedings Annual Reliability and Maintainability Symposium 1984, Jan 1984, 315-322, Hughes.

This paper describes an extension of Malcom's Bayesian analysis in which a Bayesian processor of fault information was simulated and found to greatly reduce the false alarm rate. This is an extension of the "n of m" filtering of alarms, which the authors claim does not have enough statistical independence. They show that it is wrong to heavily filter a BIT circuit, and that it is far better to apply statistical processing to the alarm output.

They define SMART BIT as any BIT that approaches the ideal of:

- 1) 100% diagnostic capability
- 2) Unambiguous fault isolation to the module level 3) Non-volatile memory
- 4) No faise alarms
- 5) The ability to detect/isolate intermittent faults

Edward J. McCluskey, S. Bozorgui-Nesbat, Design for Autonomous Test, IEEE Transactions on Circuits and Systems, November 1981, 1070-1078, Stanford Center for Reliable computing.

Technique for modifying networks so that they are capable of self test is presented. Innovation in partioning into subnetworks with sufficiently few inputs that exhaustive testing of subnetwork is possible.

Test Technology Information Center Fleet Analysis Center, Naval, Weapons Station, Corona Calif., Built-In Test (BIT) Equipment and Methods, Report 824-1619, Oct 15 1981, 150 aprox, Literature search for "BIT" etc

George Neuman, Navy Testing Technology Strategy Team, Built-In-Test Effectiveness Study, USN 1124/0679/BD14-2, June 1983, 70 aprox, Testing Technology Fleet Analysis Center NWS Corona Beach, Giordano Associates,

Test Technology Information Center, Built-In Test/ Testability Improvement Program, TTIC Fleet Analysis Center Code 8242 Corona CA 91720, TM-824-1658, Aug 83 Draft Up to date 100+ page analysis of BIT and T for all of DoD including guides, MATE, directives, standards, and their interrelationships.

Thomas G. Freund, Applying Knowledge Engineering to TPS Development, AUTOTESTCON-IEEE, October 1983, Harris

He states that most development of software production tools has concentrated on production phase which contributes between 10%-20% of the total TPS cost. An additional 50% of the costs come from the design and requirements phases of TPS. They are adapting the Programmer's Apprentice to make the TPS Assistant. This is a part of DATE(Development Assistant for TPS Engineering).

L. F. Moebus, Reducing Military Digital Testing Life Cycle Costs, AUTOTESTCON - IEEE, October 1983, General Dynamics

Looking at the digital test portion of military ATE system they find the 50% of the LCC is for operators and maintenance personnel, and only 9% is due to test program set design. "Interactive processor testing appears to be the future backbone of military digital testing." Much more-off loading of the test to the internal BIT.

Charles A Locurto, Impact of BIT on Avionics Maintainability, 1983 Proceedings Annual Reliability and Maintainability Symp, 333-338, From his PHD dissertation at South-Eastern Univ Nov 1982

A.C. MacMurray, V. D. Leonard, On-Line Monitoring Guide for Technical Personnel, TD 579, March 1983, Naval Ocean System Center- San Diego

A.C. MacMurray, V. D. Leonard, Management Personnel Performance Monitoring Guide, TD 575 March 1983, Naval Ocean System Center- San Diego, has program milestone charts for BIT.

R. K. Nair, Diagnosis, Self-Diagnosis and Roving Diagnosis in Distributed Systems, AD-A069770, Sept 1978, Univ of Illinois-Urbana

Thesis describes the type of system for which roving diagnosis is possible. This is self testing without external control. He also discusses how this minimizes testing time. This is an important concept for System Integrated Test or SMART BIT.

BIT/ETE Figure of Merit and Demonstration Techniques, 1979, RADC- Hughes BIT analysis is very costly: \$1,000,000. Has most extensive set of BIT definitions (18). Demonstration includes transient insertion.

J. McDermott, Stand-Alone Function-Generator ICS Extend Design Features, EDN, 28 #12, 61-67, 1983

In the application of design for testability, describes the use of a function generator IC able to output sine, triangle, ramp, and tone burst, either at discrete frequencies or swept. Useful for Smart BIT.

R. Owen Holbrook, BIT Detectability/Reliability in Expendable Weapons, Proceedings Annual Reliability and Maintainability Symposium, 1984

This and his 1983 paper are among the few which have equations for BIT on system performance, costs etc. He gives an example showing an equivalent increase of MTBF by 5X by having a BIT detectability of 75% at the end of 4 years for a weapon normally in storage. The effect on availability for 2000 weapons is a difference of 1400 for no-BIT and 1600 with BIT. Thus you get 200 more weapons for the cost of the BIT. He shows that there is, however, a higher maintenance cost of 14% for this example.

Bruce L. Havlicsek, Gerald G. L. Meyer. The Development and Application of System-Level Fault Models, Proceedings of Automatic Test Program Generation Workshop, 1983, IEEE Computer Society, is with the Integrated Logistics Support Division.

Meyer is with Johns Hopkins University.

This paper presents a new approach to determine conditions that ensure diagnosability properties in complex systems. The approach uses a new system-level fault model structure having both internal and observable test outcomes and allowing multiple test outcomes to be associated with each fault situation.

This paper also outlines an overall research and development program for the use of system-level fault models for real engineering applications. The program organizes the individual aspects of fault model application into a tractable and integrated proposal.

- Tim M. Strike, Gary E. Sanders, The use of EEPROMs in Embedded Computers for Avionics, Aerospace Electronics Proceedings, 1983, 611, IEEE
- R. G. Bennets, Introduction to Digital Board Testing, 1982, Crane, Russack & Company, Inc.
- V. D. Agrawal, S. K. Jain, D. M. Singer, Automation in Design for Testability, Custom Integrated Circuits Conference, 1984, AT&T Bell Laboratories

Through a well-defined set of design rules, the scan approach allows complete automation in chip testability. This paper describes a design automation system, TITUS, which automatically checks the circuit for design rules, implements the testability hardware, and generates tests.

Smith Freeman, Statistical Inference Algorithims for Automating Testing of Analog Circuits, Large Scale Systems Symposium IEEE 1982, 32-39, RCA

1983 IEEE ATPG Workshop Proceedings, IEEE Catalog #830H1878-8, 133 pages, 20 articles.

Curriculum for Test Technology, IEEE Catalog # 83CH1978-6, contains 31 pages on DFT and Test Techniques including BIT state-of-the-art report.

DIAG	DIAGNOSIS	/FAULT	DETECTION -	

G. G. Hendrix, KLAUS: A system for Managing Information and Computational Resources, SRI International, TN 230 SRI Project 1894, 34

Overview of goals and philosophy of SRI work for support systems than can be tutored in English about new subject areas. Useful in filing and retrieving information and allowing access to other tools (DBMS, planner, schedulers, report gen. etc) Excellent overview.

R. W. Allen, C. D. Chen, M. M. Ervin-Willis, K. R. Rahlfs, R. E. Tulloss, S. L. Wu, DORA: A System of CAD Post-Processors Providing Test Programs and Automatic Diagnostics Data for Digital Device and Board Manufacture, Western Electric Company, 1981 Test Conference, 1981, 555-560

Jeffry Beeler, IBM, Stanford Join Forces on AI Project, Researchers Working on AI for Diagnosing Failures in Intrasystem Hardware, November 16, 1981, COMPUTERWORLD, Describes the use of AI to diagnose intrasystem hard-ware failures in a project jointly sponsored by DEC and MIT

T. R. Addis, Knowledge Refining for a Diagnostic Aid (An Example of Applied Epistemics), International Journal Man-Machine Studies, v17, August 1982, 151-164
Epistemics is the science of communicating understanding via stored knowledge. Knowledge refining is the elimination of redundant descriptions and the exposure of contradictory or missing information, so that the essence of a structured activity can be captured for computer manipulation. Tries to describe activity like DIAGNOSTICS in the form of a hierarchy of actions. This hierarchy can be constructed by the recursive application of a pattern recognition technique(RAFFLES). Knowledge refining provides AUTOMATIC KNOWLEDGE MAINTENANCE for an expert system. See also Addis work in Maintenance Expert section.

Ramesh S. Patil etc, Causal Understanding of Patient Illness in Medical Diagnosis, IJAI 81, 893-899, MIT

Allows multivariate relation between causes and effects which varies with context. If at some level of detail two distant phenomena interact, they aggregate the description so that the two phenomena are adjacent. Aggregation can be focal (the nodes of importance) or causal.

Michael R. Genesereth, Diagnosis Using Hierarchical Design Models, (DART) 278-283, AAAI-82, Stanford University

Abstract: This paper presents a new algorithm for the diagnosis of computer hardware faults. The algorithm uses a general inference procedure to compute suspect components and generate discriminatory tests from information about the design of the device being diagnosed. In the current implementation this procedure is linear-input resolution, guided by explicit meta-level control rules. The algorithm exploits the hierarchy inherent in most computer system designs to diagnose systems a level at a time. In this way the number of parts under consideration at any one time is kept small, and the cost of test generation remains manageable. Uses common LISP with data base and inference system (MRS). It runs on VAX 11-780 in minutes regardless of the size of the model!

Hal Shubin, John Wade Ulrich, IDT: An Intelligent Diagnostic Tool, AAAI-82, 290-295 Abstract: IDT is an intelligent hardware diagnostic tool that has been successfully used to identify faults in PDP 11/03 computers. It selects and executes tests, and interprets the results. IDT is able to modify its test selection strategy on the basis of results of previous tests as well an opinions offered to it by the user. Symbolic formulas are used to represent the relationship between the test results and the broken equipment. If we assume that there is only one broken component, then set operations can be shown to be sufficiently general for combining the results of multiple tests.

Thomas Whalen, Brain Schott, Fred Ganoe, Fault Diagnosis in a Fuzzy Network IEEE 1982 Cybernetics and Society, 28-30 October 1982, 35-39

This paper presents a method for detecting and diagnosing departures from optimal output in a fuzzy network, by means of a fuzzy production system (a computer-assisted algorithm for making deductions from fuzzy premises). A human decision maker interacts with the production system through a quasi-natural language system which has been implemented in APL.

- B. Chandrasekaran, F. Gomez, S. Mittal, J. Smith, M.D. An Approach to Medical Diagnosis Based on Conceptual Structures. 6th IJCAI, 1979, Tokyo Japan. 134-142 Some principles governing the design of conceptual structures are presented. We apply the ideas to the design of MDX.
- Joseph G. Wohl, Cognitive Capability VS System Complexity in Electronic Maintenance, Cybernetics and Society Proceedings, 1982, IEEE, 370-372, ALPHATECH Condensation of another paper by Wohl
- P. P. Bennetts, Failure Diagnosis and Decision Making in Industrial Processes: A Fuzzy Set Application, IEEE, 1087-1093, General Electric

National Security Industry Association: Automatic Test Committee and Logistics Management Committee, Conference on Integrated Diagnostics. Integrated Diagnostics Conference, Feb 1983, NSIA, Tampa Florida, Most complete information on Integrated Diagnostics.

Charles Curtis National Security Industrial Association 1012-15th St NW, Suite 901, Wash DC 20005 202-393-3620

Roger T. Hartley, CRIB: Computer Fault-finding Through Knowledge Engineering Computer, March 1984, Kansas State University
Good example of maintenance expert system with ability to learn diagnostics.

Consideration for the Systematic Design of Machine Self-Diagnosis, Brian A. Kelley, Richard D. Rosen, May 1983, International Appliance Technical Conference Purdue Univ., Battelle-Columbus

Their work is still at the design stage. They are considering sensor selection and requirements. They have incorporated some of the techniques of Pau, who works at Battelle in Switzerland. Their interest is in mechanical systems diagnosis, especially jet engines.

Mike Partridge, Integrated Testing and Maintenance Technologies, December 1983, AFWAL TR-83-1183

Contract with Boeing from Air Force Wright Aeronautical Lab to define the requirements for onboard test system for the avionic suite for the tactical fighters in the 1990's. Identified improvements over current systems include better filtering of intermittent failure reports, intermittent fault isolation through the use of recorded data, more extensive use of system-level tests of mission operational data and a man-machine interface providing more information to the maintenance technician. In addition, a design concept for a fault classification expert system was developed.

L.M. Carrier et. al. Operational Flight Software Techniques for On-Aircraft Testing and Maintenance, Fifth Digital Avionics Conference, 1983. Discusses onboard fault detection and isolation for Central Integrated Test System on B-1 Bomber. Similar concepts to Partridge in preceeding reference.

R. K. Kandt, Ronald Newlon, Self-Improving Diagnostics for Automatic Test Equipment, Jan 1981, 7, ATE Seminar/Exhibit Proceedings, Electronics Test Magazine, Hughes This is the result of the MATE and RADC work with KBS. This had 43 rules in Emycin which the user could add to incrementally to improve the behavior of the diagnostics. The system would allow user to enter faults, probability, and procedures to correct the fault, along with a certainty factor. A much more descriptive phrase would be user-improvable diagnostics'.

Charles Paulson, Classes of Diagnostic Tests, 20th Design Automation Conference, 1983, 316-322, Stanford Computer Science Dept.

SUBTLE is a predicate calculus language for combinational digital systems. Work is in conjunction with IBM and Fairchild and early DART work.

B. L. Havlicsek, G. G. Meyer, A New System-Level Approach to Diagnosability, JHU/EECS-82/6, 1982, Johns Hopkins Univ/ funded by ONR and Westinghouse Does not require fault/test relationship. Permits multiple test outcomes with each fault. Internal (unobservable) test outcomes can be used. When the system has a Morphic property it becomes orders of magnitude easier to describe. This is similar to graphical fault model description. Report is highly theoretical.

John Reviore, Reliability and Maintainability Volume 6.1-Diagnostics, Institute For Defense Analysis, Volume III, 1-64, August 1983

Volume III is a summary document of some 42 other volumes of a DoD R&M improvement study. There are significant differences in definition of False Alarms(pg 4). FA impact(pg13) includes operator ignoring BIT indications, excessive LRU swapping which leads to maintenance induced failures. It reviews many of the recent reports in this field.

An air crew may need fault detection in terms of seconds. Fault isolation of environmentally mission induced problems require the system to remember why the failure occurred (pg36). Maintenance action times of 4 hours typical are accepted normally, but there would be considerable delay in maintenance in a high sortic generation schedule. Minimizing Bench Check Serviceable is important for three level maintenance concept, but is an absolute necessity for two-level concept (pg44).

Diagnostics section includes the following conclusions. Specify R&M in terms of exceeding a threshold of \$XX.XX acquisition cost per removal-free operating hour (difficult to communicate to designer pg 49). Design needs to have a flexible diagnostic system so that changes can be incorporated readily in diagnostic algorithms, screens and tolerances with minimal hardware impact. Techniques are needed to enable more concurrent hardware and software development and earlier integration of the two. CAE techniques for enhancing design for testability in support of proposed MIL-STD-XXX. Diagnostic testing in the early operations environment will reveal BIT problems. Recognize that maturation phase is a legitimate design activity and plan for it.

Operational Test and Field Maturation should include a special diagnostic data collection and analysis system to capture information on occurrences and causes in enough detail to provide a credible data base for developing and implementing engineering solutions.

Conference on Integrated Diagnostics National Security Industry Association: Automatic Test Committee and Logistics Management Committee, February 1983, 230, Latest information on BIT, etc. Partial table of contents:

Overview of Maintenance Aiding, XYZYX Corp

Technology and Technology Gaps between present and future performance aids

Artificial Intelligence Applications to Maint.	RADC	Coppola/	٠.
New look at BIT	Hughes	Malcolm	
Diagnostic Technology	NSWC	Keiner	÷
Consolidated Support System	NASC	Reagan	
Status of maintenance training simulation research in the	USAF	Pohlman	
ATE State of the art in training technology	TTA	Halley	:
Futuristic Maintenance Trainers	NTEC	Rizzo	
Integration of Automated test, maintenance aiding	11120	11220	
and maintenancetraining	Biotechnology	Post	
and maintenancetraming	Dioteciniology	1 051	
Ben Moszkowski, Reasoning about Digital Circuits, STA Stanford University Enhancement of predicate logic with interval temporal logic	gic (ITL) to acc	commodate time-	
dependent operators. Is able to describe latches, counters,	, RAM, and bit	slice.	
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John A. Swets, Ronald M. Pickett, Evaluation of Diag Signal Detection Theory, Academic Press, 1982, 253, Bolt Using Relative operating Characteristics (ROC) for gen	, Beranek, and	Newman	
have been used in signal detection, human perception, me possibly useful only to someone well into diagnosis proble		ring, etc. This is	
Alan Willsky, A Survey of Design Methods for Failure I Automatica, 12, 1976, 601-611, Pergamon Press Diagnosis, detect abrupt changes in linear systems	Detection in D	ynamic Systems,	12 12 14 12 12 12
Edward Y. Chow, Alan Willsky, Sequential Decision Rul Automatic Control Conf, 1981, 11, Chow works at Schlumberger-Doll Willsky at MIT Infor sequential decision problem. Probably Chow PHD thesis of	r and Dec., de		
B. K. Walker, Performance Evaluation of Systems that Automatic Control Conference, 1981, theoretical	Include Fault	Diagnosis, Joint	
R. N. Clark, D. C. Fosth, V. M. Walton, Detecting Inst Systems, <u>IEEE Transactions on Aerospace and Electronic</u> diagnosis			
Kazuo Nakajima, A New Approach to System Diago Communications, Control and Computing IEEE, 1981	nosis, 19th Al	llerton Conf. on	
Ruey-wen Liu, A Theory of Analog Fault Diagnosis and in of Automatic Test Program Generation Workshop, 1983, 1878-8, University of Notre Dame			:
This paper discusses two major issues of analog fault dia and simulation of faulty components. It further dis effectiveness of a testing program: test points, post-fault	scusses three	measures of the	•
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T TESTABILITY			
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Thomas W. Williams, Kenneth P. Parker, Design for Testability - A Survey, IEEE Transactions on Computers, January 1982, 2-15, 114 references, Excellent Review

- E. Shemeta, R. Spillman, Computer Aided Testability and Design Analysis, Boeing Aerospace, RADC-TR-83-257, 140 aprox
- R. Spillman, Advanced Application of the Printed Circuit Board Testability Design and Rating System, Boeing Aerospace, RADC-TR-83-291, 100+

George Neumann, Giordano Associates TESTING TECHNOLOGY (Improving Weapon System Reliability and Maintainability Study Program), Institute for Defense Analyses 1801N Beauregard St. Alexandrai VA April 1 1983

Tries to establish requirements for strong test technology program for DOD. Commercial IR&D efforts have been directed to improvements of commercial ATE, not embedded test. The services have installed over 1000 different ATE. BIT/TEST Improvement Program of Joint Services, pg3-2

Details of many aspects of program are given in this paper. They cover:

Weapon System Testability Design Techniques

CAD/ CAT Design Tools

Logistic Support Activity (LSA) Process

T Prediction and Demonstration

BIT/MTE/ATE/FOMS

Fault-Tolerant Design

On-Line Testing

Performance Monitoring Built-In-Test Maint Aids

Non-Electronic Monitoring

Off-Line Testing

ATE Applications SW ATPG Metrology/Calibration

Test Techniques

Diagnostics/Prognostics Advanced Device Testing

Non-Conventional Testing System-Level Testing

Test and Evaluation

Test Bed Demo Experimental Demonstrations

Summary of guides pg 4-28 Sponsors pg 4-31 Performing Activities pg4-32

INTERFACES TO OTHER TECHNOLOGIES from testing technology PG 4-49

CAD/CAM VHSIC RELIABILITY FIBER OPTICS

DIAGNOSTICS MECH. SYSTEMS CONDITION MONITOR

OPERATIONAL SW AI MANPOWER AND TRAINING

PACKAGING NONDESTRUCTIVE TESTING

TRADE-OFFS DRIVEN BY COST

MTBF MTTR MLOGISTIC DELAY TIME PERSONNEL

PERSONNEL SKILLS SPARES/FACILITIES/SPACE

BIT VS Off-Line Testing Organizational, Interm and Depot alloc

Acquisition Cost/Performance Capability Mobility Envr.

LIFE CYCLE COST REDUCTION of 10% to 20% with good T design pg 5-12

Anthony Coppola Artificial Intelligence Applications to Maintenance Report for OSD/IDA R&M Study, April 15 1983 review copy,

23 with 30 pg of position papers — see section 8.4.2 of this report.

Anthony Coppola, Lorraine M. Gozzo, Artificial Intelligence Applications to Testability, AUTOTESTCON 1982, IEEE, 138-142, RADC.

A. C. MacMurray, U.S. NAVY Test Technology RDT&E Plan (Rev VI), NOSC 619-225-6173, June 15 1983, 60+

Details research plan for Navy testing technology. Includes names of people and programs funded or planned. Some examples:

ATE Self Test Software

Complexity, Testability, and Fault Analysis of Electronic Systems

Testability of Structures

Testability Figures of Merit

Air Launched Missile Testability (unfunded 1983, 84 too?)

Fault Location Algorithim Investigation

Shipoboard Automatic Failure Detection and Performance Monitoring

Artificial Intelligence Applications of ATE (RCA June 1983)

Develop Analog ATPG Capability

Fault Simulation and Testability of Electronic Circuits (Complete)

Automated Shipboard Maintenance (Complete)

J. Byron, L. Deight, G. Stratton, RADC TESTABILITY NOTEBOOK June 1982, RADC-TR-82-189, Hughes,

Monumental study includes definition of terms and their sources

Giordano Associates 21 White Deer Plaza Sparta NJ 07871 Productivity Improvement. Through Testability, 1983, \$225 for 2 volumes: one for management, one for engineer,

Stephen P. Thomas, John P. Shen "A Survey of: Functional Level Testing and Testability Measures" 50 pages. Carnegie-Mellon University report CMUCAD-83-18, Nov. 1983, Dept. of Electrical Eng.

Discusses logic design techniques for testability, functional level test generation, and integration of design and testing stages with focus on the VLSI test bottleneck. They like Horstmann. (IEEE Test Conf 83) "Testability Expert" idea.

D. P. Siewiorek, R.S. Swartz, The Theory and Practice of Reliable System Design, 1982, Digital Equipment Corp., 772 pages.

Very complete technical book covering fault avoidance, fault detection, dynamic redundancy, life cycle costs, and fault statistics. Many examples of practical reliable computer system designs including VAX, IBM system 360, NonStop, Bell's ESS, Pluribus (fault tolerant multiprocessor, STAR(self test and repair), Voyager, SIFT, FMPT. It has 26 pages of references.

Model for Transient and Permanent Error-Detection and Fault-Isolation Coverage, D. C. Bossen, M. Y. Hsiao, IBM J Res Develop, Vol. 26, No. 1

The model developed in this paper allows the system designer to project the dynamic error-detection and fault-isolation coverages of the system as a function of the failure rates of components and types and placement of error checkers, which has resulted in significant improvements to both detection and isolation in the IBM 3081 Processor

Michael F. Battaglia, Angelo A. Bocchino, Jr., Innovative Maintenance Utilizing Video-disc, IEEE 1982 AUTOTESTCON, 474-477

This paper discusses methods of enhancing maintenance testing capabilities by combining "real world" video with expert diagnostic software. Battaglia issued the Navy contract on Integrated Diagnostics in 1984.

Tulin Erdim Mangir, Design For Testability: An Integrated Approach to VLSI Testing, IEEE International Conference on Computer-Aided Design - 1983, September 1983, 68-70, UCLA

Describes the 18 different testability techniques which can be used by VLSI designers and the 7 environments that they exist in. To date no trade-off techniques have been made

but "We are convinced that the use of a data base and expert system operating from that data base to be implemented in a language such as PROLOG is the most expedient way to generate alternative strategies for an integrated testing approach which is designed into VLSI systems."

Paul W. Horstman, Design for Testability Using Logic Programming, 1983 International Test Conference pg, 706-713. DFT with expert systems which can check for DFT rule violation.

- V.D. Agrawal, S.K. Jain, D.M. Singen, Automation in Design for Testability, <u>Custom Integrated Circuits Conf.</u>, May 1984, Bell Labs, TITUS = Testability Implementation and Test Generation using Scan.
- R. G. Bennetts, Design of Testable Logic Circuits, 1984 164 pages -Scan design.

Frederick G. Danner, System Test Visibility- Or Why Can't You Test Your Electronics? 1983 International Test Conference, 635-639, Grumman

C. Bellon, Ch. Robach, G. Saucier, An Intelligent Assistant for Test Program Generation: The "SUPERCAT" System, IEEE International Conference on Computer-Aided Design - 1983, September 1983, 32-33, France

Propose Intelligent Assistant to guide test designer with random logic, regular logic, RAM, PLA, and microprocessor modules. See also article by same author in International Test Conference Oct 1983.

Mark Stefik, Anal Bell, Daniel Barrow, Harold Brown, Lynn Conway, Christopher Tone, The Partitioning of Concerns in Digital System Design, Stanford University HPP-82-2, Feburary 1982

Frank Tsui, In-Situ Testability Design (ISTD)- A New Approach for Testing High-Speed LSI/VLSI Logic Proceedings IEEE, Jan 1982, 59-78, IBM Design of chips and modules with self-sufficiency for testability, despite their connection in a system.

J. Jiang, A. Tuszynski, Analog Diagnostics of Digital Circuits, <u>Proceedings: 1982 IEEE International Large Scale Systems Symposium</u> October 1982

Nonrandom soft errors can be quickly found with analog measurements. This will be very useful for SMART BIT etc.

Gary Engel, A System Approach to Fault Location, IEEE Fault Tolerant Computer Systems Conference, 1983, 400-407, Sperry-Roseville In-Unit-Cart-Test (IUCT) system is the primary diagnostic for Sperry 1100/90 system and

In-Unit-Cart-Test (IUCT) system is the primary diagnostic for Sperry 1100/90 system and uses Scan/Set logic. Average fault isolation time for this 700,000 node processor is 6 minutes. The stimulus/response library is 18 MBytes and diagnostic is 36 MBytes. Estimate that 90%+ of hardware faults will produce valid error status for items which are like single stuck at faults.

M. D. Robach, G. M. Malecha, A Computer Aided Test Analysis System: CATA, Fault Tolerant Computing Symposium 1983 408-411, France Pascal procedures: BOARDFLOW (3000 lines), flow for equipment, indiscernibility, test path determination (2300 lines), connected by a database. They have not yet added model for description of software function.

Design for Test Calculus: An Algorithm for DFT Rules Checking, Dilip K. Bhavsar, 20th Design Automation Conference, 1983, 300-307, General Electric-Syracuse, Able to deal with memory nodes, clocks, etc with one-pass algorithm.

Built-In Test/Testability Improvement Program (draft), Test Technology Information Center Fleet Analysis Center, TM-824-1658, Dec 1982 (August 1983), 120+

Z.F. Huang, Chen-Shang Lin, Ruey-Wen Liu, Node-Fault Diagnosis and a Design for Testability, IEEE transactions on Circuits and Systems, May 1983, theory, equations

Ch. Robach, Ph. Malecha, G. Michel, Computer Aided Testability Evaluation and Test Generation, 1983 International Test Conference - Proceedings, 1983, 338-345, IEEE Robach is with IMAG Laboratory Malecha and Michel work for E. P. Schlumberger

C. Bellon, Intelligent Assistant for Test Program Generation, IMAG March 1984, IEE #232, page 166.

Shunsuke Miyamoto, Takao Mishida, Tokinori Kozawa, Fumiya Tada, TRUE: A Fast Detectability Estimation System, ICCAD, 1983, Hitachi Ltd

IF	- INTERMITTENT FAILURES	
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Anton T. Dahbura, Gerald M. Masson, A New Diagnosis Theory as the Basis of Intermittent-Fault/Transient- Upset Tolerant System Design, 353-356, 1982 Fault Tolerant Proceedings IEEE. The Johns Hopkins University Grant from Fairchild. Greedy Diagnosis outcomes are used for all they are worth. Can work from limited information of transient faults.

Soft Error Testing, 1980 IEEE Test Conf., 137-150, Soft errors in RAM

Jacques Losq, Testing for Intermittent Failures in Combinational Circuits, 3rd USE JAPAN Computer Conference, 1978, 165-170

Is a study of the efficiency of test procedures to detect intermittent failures in combination circuits. When little or no information is available, then the best method to test for intermittent failures is simply to repeat the test designed for permanent failures. A simple way of estimating the number of repetitions needed to yield a high detection rate is given.

E. B. Lee, R. F. Stover., Training A Logic Network To Do "Fault Detection In Electronic Circuits," Curriculum for Test Technology, Nov 1983, IEEE 83CH 1978-6, pages 148-161. This work at University of Minnesota is the only AI type work on faults which are out of specification rather than total failure. Computer programs were made to train six different pattern recognition schemes with five decision algorithms on three simulated circuits (linear and non-linear). The Arkadev method results look promising, even without the use of a computer.

C0	- COSTS LCC	

B. Berazi, F. Fenoglio, G. Turconi, Diagnostic Coverage as Life Cycle Cost Parameter, Reliability in Electrical and Electronic Components and Systems, E. Lauger, J. Moltoft, North-Holland, 1982, pg 1046-1050.

Analyzes the costs of 7 types of failures to arrive at optimal diagnostics. Great book too.

Edward F. Toohey, Alberto B. Calvo, Cost Analyses for Avionics Acquisition, 1980 Proceedings Annual Reliability and Maintainability Symposium, pg 85-90.

Robert E. Lee, Logistical Impacts Within the Cost Analysis Community, Armed Forces Comptroller, Spring 1983, pg 18-20. This information serves as the primary LCC cost weights.

B.S. Blanchard, Logistics Library Reference List: Suggested Reference List for the Logistics Practitioner, Logistics Spectrum, Fall 1983, pg 40-45.

8.3 LIST OF INTERVIEWS

The following people were interviewed or contacted in person or by telephone during this contract. They are in categories of Industry, Academic and then Government.

INDUSTRY

Battelle, Switzerland L. F. Pau

BIT Inc., Manassas, Virginia John Cunningham

Boeing John Rivore - IDA Study

Bruce Wilson - AI Manager

Bolt Beranek and Newman Dr. Alper Caglayan Cambridge, MA

Robert Schudy

Digital Equipment Corp. Hal Shubin - IDT

General Electric John W. Lewis, Ph.D

General Dynamics John Hinchman, Gordon England

GenRad Dr. Geoffrey Bunza

Grumman Robert Hong

Hughes Dr. Doug Partridge, Ed Kim

Lockheed Palo Alto Research Lab W. Walton Perkins

McDonnel Douglas Jim Miller St. Louis, MO

Magnavox, Ft. Wayne Ind. Michael Arington

RCA Eric Braude, Johnathen Gaev - AI/ATE

SoHar Inc. H. Hecht L.A. California

Sperry Dave Persans, Jim Caporla

Tektronix John Ulrich - had been DEC-IDT

Texas Instruments Steve Morris - PEAM

XEROX PARC Johan de Kleer Palo Alto, CA

ACADEMIC

Standford University Dr. Mike Genereseth

MIT Dr. R. Davis

Ohio State University Dr. Chandrasekaran - Diagnostics
University of Illinois Dr. R. Michalski - Machine Learning

UCLA Dr. Mangir - VLSI Testability

GOVERNMENT Wright Patterson AFB AFSD Don Allen Naval Air Engineering Center N.J. Jerry Kunert AI/ATE NRL AI Research Center Rickie Cantone (Now with Automated Reasoning Corp - Sunnyvale, CA) Naval Surface Weapons Center William Keiner Naval Training Equipment Ctr. Bob Ahlers Orlando, Florida Human Factors Lab Automatic Knowledge Acquisition
Wright Patterson AFB AFSD Don Allen Naval Air Engineering Center N.J. Jerry Kunert AI/ATE NRL AI Research Center Rickie Cantone (Now with Automated Reasoning Corp - Sunnyvale, CA) Naval Surface Weapons Center William Keiner Naval Training Equipment Ctr. Bob Ahlers Orlando, Florida Human Factors Lab Automatic Knowledge
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8.4 SUMMARY OF RELEVANT 1983 TEST STUDY RECOMMENDATIONS

8.4.1 Testing Technology

Improving Weapon. System Reliability and Maintainability Study Program), Record Document D-41, 1983. Institute for Defense Analyses.

Tries to establish requirements for strong technology program for DOD. Commercial IR&D efforts have been directed to improvements of commercial ATE, not embedded test. The services have installed over 1000 different ATE.

Details of many aspects of program are given in this paper. They cover:

Weapon System Testability Design Techniques

CAD/CAT Design Tools

Logistics Support Activity (LSA) Process

T Prediction and Demonstration

BIT/MTE/ATE/FOMS

Fault-Tolerant Design

On-Line Testing

Performance Monitoring Built-In-Test Maint Aids

Non-Electronic Design

Off-Line Testing

ATE Applications SW ATPG Metrology/Calibration

Test Techniques

Diagnostics/Prognostics Advanced Device Testing

Non-Conventional Testing System-Level Testing

Test and Evaluation

Test Bed Demo Experimental Demonstrations

Conclusions

- 6.1 TRADITIONAL WEAPON SYSTEM RELIABILITY AND MAINTAINABILITY DESIGN TECHNIQUES ARE NO LONGER SATISFACTORY
- 6.2 IMPROVEMENT IN THE TECHNOLOGY BASE IS REQUIRED
- 6.4 THE MANAGEMENT OF TESTING TECHNOLOGY REQUIRES IMPROVEMENT

Recommendations

- 7.1 INITIATE A MAJOR WEAPON SYSTEM DESIGN TECHNOLOGY PROGRAM, WHICH INJECTS TESTING TECHNOLOGY INTO THIS DESIGN PROCESS
- 7.2 INVEST IN EXPANDING THE TESTING TECHNOLOGY BASE TO PROVIDE "OFF-THE-SHELF" PROVEN ALTERNATIVES FOR USE IN WEAPON SYSTEM DESIGN
- 7.3 INSTITUTIONALIZING THE TRANSITIONING AND UTILIZATION OF TESTING TECHNOLOGY
- 7.4 INITIATE A SERIES OF ACTIONS TO IMPROVE TESTING TECHNOLOGY MANAGEMENT

A summary of their analysis is in table 8.4.1.

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Table 8.4-1 Test Technology Prioritization

8.4.2 ARTIFICIAL INTELLIGENCE APPLICATIONS TO MAINTENANCE

Technology Working Group Report (IDA/OSD R&M Study), Anthony Coppola, USAF, Working Group Chairman, Institute for Defense Analyses, IDA Record Document D-28, August 1983.

EXECUTIVE SUMMARY

The maintenance of modern military systems employs a variety of automation. Built-In-Test (BIT) provides on-line fault detection and some isolation, Automatic Test Equipment (ATE) is indispensible at intermediate and depot repair stations, and automated maintenance aids and trainers abound.

These developments were designed to speed maintenance and to compensate for declining skill levels in the maintenance force. They are currently far from satisfactory. Modern maintenance is characterized by excessive false alarms and unnecessary removals at all levels of maintenance.

The results of these deficiencies are long maintenance times, resources wasted in unnecessary or inefficient maintenance actions, and systems out of action which need not be. Correcting these problems would therefore provide both an economic advantage and a force multiplier.

To create quantum improvements in maintenance will require the application of radical changes to the technology. One possibility is the application of Artificial Intelligence (AI) techniques to maintenance. AI is beginning to see application to practical problems in many disciplines, and hence is potentially capable of relatively rapid implementation into military systems.

At present, DoD efforts in applying AI to maintenance are small and exploratory.

The task of the Artificial Intelligence Applications committee was to examine the opportunities for applying AI to maintenance, assess the costs, risks, and development times required, and provide recommendations to the DoD for action.

The committee's recommendations are detailed in section 9 of this report, and in the attached position papers. A summary follows:

1. The DoD should take advantage of the relative maturity of the technology for creating expert systems. Specific applications of maintenance expert systems should be started immediately, and multi-application maintenance experts developed and standardized.

Develop maintenance expert systems immediately for current maintenance applications where the existing ATE has been inadequate. Permit these systems to be built in any convenient language and architecture, except that test programs generated for outside use would be in ATLAS.

Develop versatile maintenance experts for specific domains (e.g., digital electroncs) capable of use in different systems. System specific data would be required for each application, but the knowledge base would remain the same.

Develop a tool to automate the creation of the system specific data required by the maintenance experts described in the preceding paragraph.

- 2. Develop "smart" built-in-test (BIT) systems to reduce false alarms, identify intermittent failures, improve BIT coverage.
- 3. Fund applied research in AI for maintenance to improve expert system designs and to develop other promising applications. Topics could include automating creation of maintenance manuals, applications to maintenance information systems, AI based automatic test pattern generation (ATPG), VHSIC design for testability, knowledge based computer aided instruction (CAI), and self-improving diagnostics.
- 4. Foster an integrated DoD-Industry approach. Coordinate DoD activity through a tri-service working group under the existing JLC panel on automatic testing. Encourage private avenues of development; continue to support industry IR/D in the area.

8.4.3 INTEGRATED TESTING AND MAINTENANCE TECHNOLOGIES

Robert O. Denney, Mike J. Partridge, Roger B. Williams, Boeing Aerospace Company Avionics Laboratory (AFWAL/AAAS-2) Air Force Wright Aeronautical Laboratories, F33615-81-C-1517, AFWAL-TR-83-1183, December 1983.

The Integrated Testing and Maintenance Technologies study effort defined requirements for the onboard test and maintenance system for the 1990's tactical fighter. These requirements are documented in the ITM system specification.

This report provides the background and analyses that led to the ITM system requirements. Problems with test and maintenance systems were analyzed and current tactical fighters were evaluated to determine where improvements could be made. The anticipated avionic architecture and mission for the 1990's tactical fighter were evaluated to determine new demands on the test and maintenance system. From these, the requirements for ITM were developed by starting at the highest level, defining the required capabilities, and specifying requirements down to the level of what tests to perform and how the system operates.

The system as specified is primarily a test data collection system, with tests provided by the subsystem and test data processing provided by the subsystem software. The improvements over current system provided for in the specification include—

- a. Better filtering of nuisance alarms from the pilot. This includes filtering of intermittent failure reports when they do not affect the mission and suppression of reports of noncritical failures during critical flight phases.
- b. Better isolations of intermittent faults. This is accomplished by inflight recording and postflight processing of fault data and associated data, including equipment temperature, aircraft flight dynamics, equipment operating modes, and subsystem modes.
- c. Incorporation of more extensive system-level tests. These include reasonableness tests of mission operational data, statistical tests on the innovation vector from a Kalman filter, and voter tests where applicable.

- d. Variable test tolerances. For those tests that are measurements of performance against limits (e.g., power supply voltage, transmitter power) the limits are stored in the system software instead of in the subsystem hardware.
- e. Interactive participation by the maintenance technician. Besides selecting the test sequences and observing results, the maintenance technician receives test data and the diagnostic decisions the system used in isolating a problem. These are used by the maintenance technician along with the capability to access additional test data to isolate the difficult problems. The interaction with the system provides "on the job training" for the maintenance technician instead of relegating him to the role of a "button pusher."
- f. Offline use of test data. Test data that will help the depot to isolate failures or determine the cause of them is stored for access at the depot. This data can also be used to create a failure history to develop failure trends.

Another conclusion of the ITM effort is that artificial intelligence, expert systems, is potentially useful for application to testing and maintenance problems and appears practical for postflight analysis applications in future generation tactical fighter aircraft. The benefit of an expert system is that it can help solve problems normally requiring the experience of the system designer or an experienced maintenance technician.

While the use of expert systems appears beneficial and practical, it still requires more development work before it can be applied on a tactical fighter development contract for integration with its avionic system. No systems with AI have yet been developed for avionics, and most miltary applications are just now getting started. This makes specification and management of its development for a project difficult and risky. Continued development of the expert system described in this study or a similar development effort on an R&D basis is recommended as a risk reduction measure before insertion in a mainstream program.

8.4.4 COMPUTER AIDED TESTABILITY DESIGN ANALYSIS

E. Shemeta, R.Spillman, Boeing Dec 1983, RADC TR-83-257. Condensed as paper authored by Thomas L. Fennell, Thomas A. Nicolino, Reliability and Maintainability Symposium 1984, pages 1-6.

Summary of Results

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A design plan for a CAT system has been developed that naturally fits into the flow of the engineering design process and is integratable with existing CAD systems. This design plan requires the development (or refinements) of five CAT modules; these modules are:

- 1. Testability Allocation Module
- 2. Test Point Location Module
- 3. Testability Analysis Module
- 4. BIT Selector Module
- 5. Automatic Test Program Generation Module

These CAT modules, when integrated into existing CAD systems, will provide a designer with an interactive design tool to ensure that testability is incorporated into the design process.

A key to an effective CAD/CAT system is the utilization of detailed design information that typically exists in the databases of today's commercial CAD systems. Much of the design information in that database is useable for CAT design tasks; although, when CAT functions are added, this database must be expanded to include additional information required in the design for testability process. The structure of the existing databases and their management systems are adequate to support this expansion. For example, standard designs of commony used logic or functional structures are saved in the CAD database for use by other designers. Functional structures with proven, effective, BIT, can also be stored, along with appropriate notational information, in the same CAD database to provide useful inputs to the testability programs. Testability unique functions, such as BIT selection, may require separate files, but there should be no problem in using the CAD system's file and data base handling software to service those needs.

Currently no commercially available CAD system performs all these functions on an integrated basis. A number of CAD systems have been developed for semiconductor LSI/VLSI chip design. Some automatically incorporate BIT, such as Level Sensitive Scan Design (LSSD), into a design. Such systems are not operational at the Printed Circuit Board (PCB) or unit level design, due to limitations of currently available parts. For example, the testability of a microprocessor based design is dependent upon the firmware and software as well as the hardware interconnections. However, for a very broad spectrum of design, the CAD/CAT design plan described here is practical, simple to implement, and an improvement over existing manual methods.

The use of engineering workstations, with continuation of schematic based CAD tools, is now emerging as the primary design tool for the electronics engineer. The CAT approaches described in this document are compatible with this trend. Some of the CAT

modules needed already exist or have been developed to a point that a practical production version could be developed economically. For instance, many ATPG programs are available and in use in present CAD systems; testability analysis approaches have been developed by Grumman (non-automated for PCB's only), Boeing (automated system testability) and Comsat General Corporation (a commercial add-on to TEGAS). Further details of the recommended CAT approach are presented in section 3.0, CAT Design Plan, and section 5.0, CAT Guidelines.

MODULE	INPUTS	BASIC FUNCTION	OUTPUTS
Testability Allocation	FUNCTIONAL BLOCK ORIENTED SYSTEM DESIGN OR SUBSYSTEM PARTITIONED CONCEPTUAL DESIGN	ASSIGN SYSTEM LEVEL TESTABILITY FOM'S TO FUNCTIONAL OR SUBSYSTEM BLOCKS BASED ON CONCEPTUAL DESIGN INPUTS AND CONSTRAINTS BY SYSTEM DESIGN ENGINEER	T FOR EACH FUNCTIONAL OR SUBSYSTEM BLOCK
Testability Analysis	LOWEST LEVEL TESTABILITY FOM VALUES (1) AVAILABLE; DEVICE, CIRCUIT, PCB; OR SUBSYSTEM AND LOWEST LEVEL DESIGN DESCRIPTION FROM CAD DATABASE	CALCULATE HIGHER LEVEL TESTABILITY (1 or T) BASED ON DESIGN STRUCTURE	t or T FOR EACH IDENTIFIED HARDMARE NODE (1.e. CIRCUIT, PCB, SUBSYSTEM OR SYSTEM)
Test Point Location	CIRCUIT OR SUBSYSTEM DESIGN DESCRIPTION FROM CAD DATABASE THAT INCLUDE DESIGNER PLACED TEST POINTS	CALCULATE PARAMETRIC TESTABILITY DATA TO ALLOW DESIGNER TO ANALYZE TESTABILITY OF EACH DEFINED CIRCUIT/SUBSYSTEM NODE	WEIGHTED CONTROLLABILITY AND OBSERVABILITY DATA ON EACH CIRCUIT/SUBSYSTEM
BIT Selector	DESIGN AND LIBRARY INFORMATION IN CAT PORTION OF CAD DATABASE AND TESTABILITY REQUIREMENTS INPUTS FROM DESIGNER	INTERACTIVE DESIGNER TOOL TO PROVIDE BIT CAPABILITY AND DESIGN INFORMATION TO AID THE DESIGNER IN CHOOSING THE BEST BIT APPROACH FOR A GIVEN APPLICATION	BIT DESIGN AND CAPABILITY DATA: SUBSYSTEM AND DETAIL DESIGN LEVELS
ATPG	DETAILED DESIGN FROM CAD DATABASE AND SPECIFIC TEST DIRECTIONS: DATA AND LIMITS FROM DESIGNER	USING PATH SENSITIZATION TECHNIQUES (e.g. D-ALGORITHM), GENERATE THE SET OF TEST VECTORS AND OUTPUTS FOR A GIVEN DESIGN ALONG WITH TEST QUALITY DATA	TEST SET (TEST VECTORS) DATA AND GOOD OUTPUTS PLUS RELATED TEST QUALITY DATA (e.g. FAULT COVERAGE)

Table 8.4-2 CAT Modules: Description Summary

9.0 GLOSSARY OF TESTABILITY TERMS

The sources of some definitions are given in parentheses following the definition. The source identification are from the MATE document:

ATG Industry ATG Glossary, Report of Industry Ad Hoc ATE Project for the

Navy, April 1977

IEEE Standard Dictionary of Electrical and Electronics Terms, IEEE Std

100-1972

IEEE/FTC Interim IEEE Technical Committee on Fault Tolerant Computing Dic-

tionary of Terms.

I/JS Industry/Joint Services Automatic Test Project Final Report

TR-3826 A Framework for Designing Testability into Electronic Systems

MIL-STD-721B Definition of Effectiveness Terms for Reliability, Maintainability

Human Factors and Safety

MIL-STD-1309B Definitions of Terms for Test, Measurement and Diagnostic Equipment

MIL-STD-2077 Test Program Sets, General Requirements for

Ambiguity group. The group of maintenance replaceable units which may contain faults which result in the same fault signature; also the number of units in such a group (TR-3826).

Automatic test equipment (ATE). Equipment that is designed to conduct analysis of functional or static parameters to evaluate the degree of performance degradation and that may be designed to perform fault isolation of unit malfunctions. The decision making, control, or evaluative functions are conducted with a minimum reliance upon human intervention (MIL-STD-1309B).

Availability. A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time (MIL-STD-721B). Availability is the probability of a system readiness over along interval of time (TR3826).

BIT false alarms. A false alarm occurs if a component is declared defective and it is found in separate off-line test to be failure free.

Built-in test (BIT). A test approach using BITE or self-test hardware or software to test all or part of the unit under test (UUT) (MIL-STD-1309B).

<u>Built-in test equipment (BITE)</u>. Any device which is part of an equipment or system and is used for the express purpose of testing that equipment or system. BITE is an identifiable unit of the equipment or system (MIL-STD-1309B).

Dependent fault/dependent failure. A fault which is caused by the failure of an associated item (MIL-STD-721B).

<u>Design fault</u>. A design characteristic of either hardware or software which causes or materially contributes to equipment malfunction independent of the presence of hardware failures (TR3826).

<u>Design for testability (DFT)</u>. A design process or characteristic thereof such that deliberate effort is expended to assure that a product may be thoroughly tested with minimum effort, and that high confidence may be ascribed to test results (TR3826).

False alarm. An indicated fault where no fault exists. (Does not include good items in an ambiguity group.) (MIL-STD-1309B).

Fault. A physical condition that causes a device, component, or element to fail to perform in a required manner; for example, a short-circuit or a broken wire (IEEE). A degradation in performance due to detuning, maladjustment, misalignment, failure of parts, and so forth (MIL-STD-1309B). The causative failure of a lower level assembly within the unit under test (ultimately a fault may be traced to a physical change of a component of the system) (I/JS).

<u>Fault coverage</u>. An attribute of a test or test procedure expressed as the percent of faults of the total fault population which that test or test procedure will detect (TR3826).

Fault detection. A process which discovers or is designed to discover the existence of faults; the act of discovering existence of a fault (TR3826). One or more tests performed to determine if any malfunctions or faults are present in a unit (MIL-STD-1309B).

<u>Fault isolation</u>. Where a fault is known to exist, a process which identifies or is designed to identify the location of that fault within a small number of replaceable units (TR3826). Tests performed to isolate faults within the unit under test (MIL-STD-1309B).

Observability. An attribute of equipment design which describes the extent to which signals of interest may be observed (TR-3826).

On-line test. Test of a UUT in its operational environment (MIL-STD-1309B).

On-line testing. Testing of the unit under test in its operational environment (see interference testing and noninterference testing (MIL-STD-1309B).

On-line test equipment. Equipment used to perform tests on a UUT while the unit is in its normal operating environment (ATG).

Readiness. A state of being ready to successfully perform or being in the act of successfully performing a defined mission (TR-3826).

Readiness test. A test specifically designed to determine whether an equipment or system is operationally suitable for a mission (MIL-STD-1309B).

<u>Self-test</u>. Built-in test (TR3826). A test or series of tests, performed by a device upon itself, which shows whether or not it is operating within designed limits. This includes test programs on computers and automatic test equipment which check out their performance status and readiness (MIL-STD-1309B).

<u>Self-test capability</u>. The ability of a device to check its own circuitry and operation. The degree of self-test is dependent on the ability to fault detect and isolate (MIL-STD-1309B).

SIT (System Integration Test). Built-in system test that is centrally integrated, i.e., BIT data is analyzed through a central computer before Fault Detection/Isolation can be determined.

Testability. A design characteristic which allows the status (operable, inoperable, or degraded) of a system or any of its subsystems to be confidently determined in a timely fashion (TR-3826). Testability attempts to quantify those attributes of avionic system designs which facilitate detection and isolation of faults that affect system performance. Testability has been defined as "the characteristic of a design which allows the status of a system or any of its subsystems to be confidently determined in a timely fashion." This definition should be expanded to include the concept of isolating and repairing detected faults in a confident and timely fashion so as to minimize repair time. Testability is the unambiguous isolation of a fault to an appropriate level of replaceable equipment such that the proper maintenance is implemented with a minimum expenditure of time and resources. Specification of that appropriate level is a most important consideration, which must be addressed early in the design cycle. (Subtask A-3 Design for Testability, Final Report. U. S. Government Printing Office, 1977, 727-156/1-3, p 35.)

Testability reflects the susceptibility of a PCB to the detection of all faults, to rapid and accurate isolation to the faulty component without ambiguity and to functional test and thereby verification of PCB performance as specified and/or required. (testability Investigation Attachment IV to Interim Report, Manufacturing Methods and Technology for Digital Fault Isolation for Printed Circuit Boards, Contract No. DAAK40-78-C-0290.)

Testability, inherent. A hardware testability design characteristic which does not include consideration of test stimulus/response data.

Testability Relative Overhead (Burden). The incremental increase in the prime functional configuration, as a proportion of the unburdened prime equipment attribute, to achieve the fault isolation performance (probability of isolation) required.

9.1 LIST OF ABBREVIATIONS AND ACRONYMS

AI artificial intelligence

AIAM artificial intelligence applications to maintenance (see 8.4.2)

ARINC Aeronautical Radio Inc.
ATE automatic test equipment

ATLAS Abbreviation Test Language for All Systems

ATPG Automatic Test Program Generation

BIT built-in test

BITE built-in test equipment

CAPDT computer-aided preliminary design for testability

CND cannot duplicate

CRIB computer retrieval incidence bank

CSS consolidated support system

C3I command, control, communication, and intelligence

DEC Digital Equipment Corp.
DFT Design for Testability

EEPROM electrically eraseably programable read only memory

ETE electronic test equipment

FA false alarm

FOM figure of merit
GE General Electric

H/W Hardware

IBM International Business Machines

IC Integrated Circuit

IDA Institute for Defense Analysis

IDEAL Incorporation of Diagnostic Experience through Automated Learning

ITM Integrated Testing and Maintenance

LCC life cycle cost
LISP an AI language
LRU line replaceable unit

LSSD Level Sensitive Scan Design

MATE modular automatic test equipment - Air Force

MTBF mean time between failures

PROLOG an AI language

R&M reliability & maintainability

RADC Rome Air Development Center (USAF)

RTOK retest OK

SID Self-Improving Diagnostics
SIT System Integrated Test

STAMP System Testability and Maintenance Program

S/W Software

SPR Software Problem Report
SRU shop replaceable unit
STE special test equipment

TPS Test Program Set (ATE Hardware and Software)

V&V verification & validation

VAX computer manufactured by DEC VHSIC Very High Speed Integrated Circuit

VLSI Very Large Scale Integration

MISSION

Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence $\{C^3I\}$ activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices $\{POs\}$ and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

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